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FROM THE EXECUTIVE DIRECTOR

Fiscal 2023 was a year of leadership. The Institute for Quantum Computing (IQC) emerged from our 20th anniversary year with the determination and motivation to sustain our excellence within academia and industry across the Canadian and international quantum ecosystems. IQC is focused on solidifying our quantum connections by positioning our researchers and alumni to lead the way into a global quantum-ready landscape.

Thanks to the continued commitment and support of the Federal Government, IQC and Canada stand among the top quantum centres worldwide. Over the past year, we have contributed to global quantum knowledge with 162 published papers, 125 presentations and 197 ongoing, international collaborations. Our graduate program attracted 207 students from across the globe, and the first cohort of students graduated from our new course-based Master of Science in Quantum Technology, a program tailored to producing highly qualified professionals to meet the needs of the growing quantum industry.

IQC is the bedrock of the Canadian quantum community, with our impact extending far beyond Waterloo. IQC alumni and past members now hold faculty positions at every centre of quantum study in Canada, including: British Columbia, Sherbrooke, McGill, Ottawa, Toronto, Simon Fraser, McMaster, Guelph, Moncton, Carleton and Mount Allison. Internationally, the list of universities with IQC trained faculty includes Harvard, UT Austin, Oxford, UCLA, Maryland (QUiCS), Tsinghua, NUS (Singapore), ETH Zurich, Delft, UT Sydney and Duke to name a few. Many of these past students and post-docs have directed their students to further studies at IQC, strengthening Canada's reputation as the place for advanced quantum information science and technology work.

The academic successes of IQC combined with the entrepreneurial spirit at the University of Waterloo has helped foster Waterloo's Quantum Ecosystem — an environment where industrial growth is exponential in the quantum sector. IQC's community is highly immersed in startups, with 45% of IQC faculty members involved in or founding their own companies. Additionally, a considerable number of IQC's postdoctoral fellows, research assistants, and graduate students are also involved with quantum startups either during or following their time as IQC members. These startups are creating positive disruption within Waterloo Region. For example, in May 2022, one startup generated $7M in series A funding, which included Sandbox AQ (an Alphabet spin-off) as an investing partner, while other startups are actively hiring, awaiting regulatory approvals, or routinely generating intellectual property. IQC has a rich history of advancing the quantum ecosystem in Canada and will continue leading the quantum landscape toward a bright future.

As IQC's Executive Director, I look forward to continuing this journey of innovation along with the Government of Canada. Thank you for your continued support.

Sincerely,

Norbert Lütkenhaus
Executive Director, Institute for Quantum Computing
University of Waterloo

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EXECUTIVE SUMMARY

Established in 2002, the Institute for Quantum Computing (IQC) has emerged as a catalyst for discovery in Canada, delivering breakthroughs in quantum information science and quantum technologies. These discoveries have attracted engaging faculty, brilliant students, and investments from around world. Fundamental research paired with the entrepreneurial environment at Waterloo has created a culture where research leads to commercialization that benefits all Canadians.

In support of its important work, in 2022 IQC was awarded $10M in funding by the Government of Canada to be used over two years. This funding has supported five key objectives and the great strides IQC has made toward achieving each of them.

Highlights from the 2022-2023 year, include:

- Attracted almost $29,300,000 in funding, reaching a combined total of almost $130,000,000 in the last 4 years
- Recruited one new faculty member and five research associates
- Welcomed 13 new postdoctoral fellows and reappointed nine more fellows
- Published 162 papers in peer-reviewed journals
- Attained over 86,000 cumulative citations
- Delivered 122 talks at conferences and colloquia across Canada and the globe with more than 197 ongoing collaborations
- Attracted a new high of 558 applications from across Canada and the world to our graduate programs
- Received over 660 awards/fellowships/scholarships for IQC graduate students
- Hosted seven workshops, 78 seminars, 10 colloquia, and sponsored 11 external scientific programs
- Garnered over 205,000 views and over 42,500 hours of watch time on IQC's YouTube Channel from viewers all over the world

IQC, in collaboration with the Government of Canada and our other partners, is actively constructing Canada's quantum information economy in the Waterloo Region. By utilizing its world-leading infrastructure and exceptional scientific expertise, IQC has established the nation's leading market-oriented ecosystem for developing, constructing, and evaluating quantum information services and devices. As the quantum ecosystem evolves within, both Waterloo Region and Canada, this growth will further reinforce our regional and national reputations as global frontrunners in quantum science and technology.

INSTITUTE FOR QUANTUM COMPUTING

IQC at the University of Waterloo was founded in 2002 to drive the development of quantum information science and technology within Canada. The founding vision for IQC was bold: **position Canada as a leader in research and provide the necessary infrastructure for Canada to emerge as a quantum research powerhouse.** Today, IQC stands among the top quantum information research institutes in the world. Experts in all fields of quantum information science and technology come to IQC to conduct research, share knowledge and encourage and support the next generation of scientists, mathematicians, and engineers.

IQC is leading the next great Canadian technological revolution. Quantum discoveries and applications developed in IQC labs are creating the foundation for next generation technologies, based on quantum information research conducted right here in Canada.

None of this would be possible without the visionary leadership and investments of Mike and Ophelia Lazaridis, the Government of Canada, and the University of Waterloo. This strategic private-public partnership has accelerated the advancement of quantum information research and discovery in Canada, and around the globe.

Vision & Mission

IQC's vision is to harness the power of quantum mechanics for transformational technologies that benefit society and become the new engine for economic growth in the 21st century and beyond.

IQC's mission is to develop and advance quantum information science and technology at the highest international level through the collaboration of computer scientists, engineers, mathematicians and physical scientists.

Strategic Objectives

IQC is guided by strategic objectives developed in partnership with the Government of Canada:

1. To establish Waterloo as a world-class centre for research in quantum technologies and their applications.
2. To become a magnet for highly qualified personnel in the field of quantum information.
3. To be a prime source of insight, analysis and commentary on quantum information.

FUNDING OBJECTIVES

2022-2024

In April 2022, IQC was awarded $10M over two years from the Government of Canada in support of the following five objectives:

A. Promote knowledge in quantum information science and technology.

B. Provide opportunities for students to learn and apply new knowledge.

C. Raise awareness and knowledge of quantum information science and technology in both the scientific community and amongst Canadians more generally.

D. Position Canada to take advantage of economic and social benefits of research by seizing opportunities and commercializing breakthrough research.

E. Brand Canada as a place to conduct research in quantum information science and technologies.

The activities planned and undertaken by IQC with the support of the Government of Canada over the past decade has positioned Canada to take full advantage of socioeconomic benefits of quantum research and technology. What follows is progress achieved by IQC in the 2022-2023 year.

Objective A

Promote knowledge in quantum information science and technology.

Expected Result: Increase knowledge in quantum information and technology.

Planned activities:

- Leveraging talent from across three University of Waterloo faculties — Engineering, Mathematics and Science — researchers will continue IQC's collaborative and interdisciplinary research agenda in quantum computing, quantum communication, quantum sensors and quantum materials.
- Publishing research results in globally recognized journals.
- Recruiting new faculty members, research assistant professors and research associates.
- Contributing to the national and global quantum information science and technology community through organizing and participating in conferences both in Canada and abroad.
- Continuing to outfit and maintain the Quantum Nano Fabrication and Characterization Facility (QNFCF) to enable fabrication of quantum-enabled technologies.
- Updating and maintaining laboratory space in the Research Advancement Centre (RAC) buildings.
- Continuing effective and relevant relationships with current research partners.
- Seeking out new partnerships that will advance IQC's mission and strategic objectives.

Research Publications and Citations

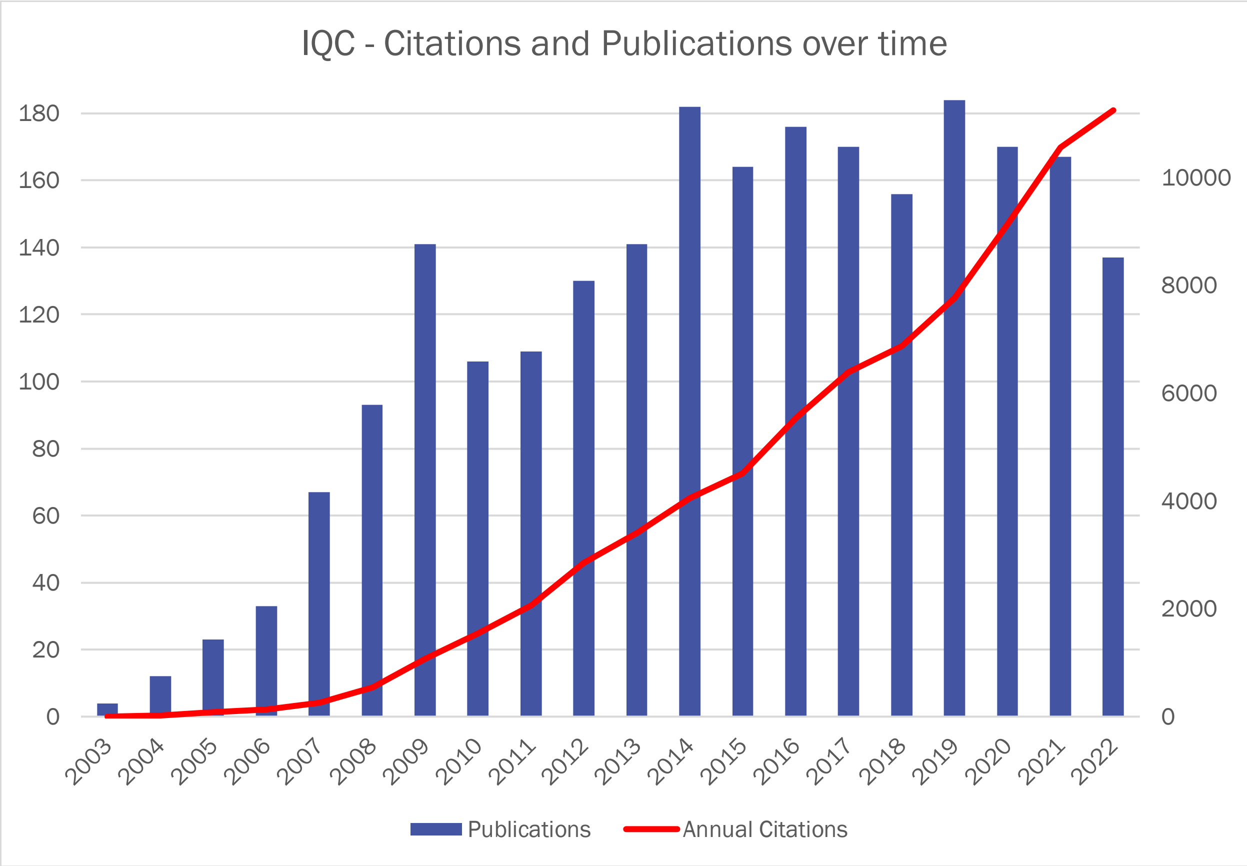
In 2022-2023, IQC researchers collectively published 162 papers in peer-reviewed journals, bringing the cumulative number of publications to 2765[1] since 2002. Several papers appear in prominent scientific publications including Science, the Nature family, the Journal of Mathematical Physics and Physical Review Letters. Below is a summary of articles published in prominent journals since 2016. A full list of all papers published this year can be found in Appendix B beginning on page 72.

Prominent Publications	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**
Family of Nature Journals	9	9	4	9	12	11	9
Physical Review Letters	11	6	8	15	8	10	4
Science			1			2	
Journal of Mathematical Physics	3	4	5	1	3	1	2
FOCSs	1			9	1		
STOC	2	1	1	1	3		1
QIP	5	10	11	11	5	7	1

Further analysis reveals that 67.5% of IQC papers (from 2017 through to the present) have been published with international collaborators from leading universities and institutes including Massachusetts Institute of Technology (MIT), University of Maryland, Delft University of Technology, as well as other prominent Canadian quantum institutions including Université de Sherbrooke, University of British Columbia and University of Toronto. IQC also collaborates with non-academic researchers including publications with Zapata Computing, D-Wave Systems and Microsoft Research.

[1] Includes Web of Science as well as journals from Scopus that are not indexed in Web of Science.

Citations are also an important indicator of the influence of published research. As of March 31, 2023, the number of cumulative citations from IQC's published papers reached 86,511. The adjacent table highlights the large increases in IQC citations, highlighting the significant impact of IQC researchers on global quantum research.



Source: Web of Science; Search: AD= ((Inst Quant* Comp*) OR IQC) and ad = waterloo + Scopus Journals not indexed in WoS: Search: AFFIL(Inst* Quant* Comp*) AND AFFILCITY (waterloo); timespan 2015-2022. Data pulled on March 31st of each fiscal year.*

Research Highlights: Advancing Quantum Knowledge and Understanding

The following stories highlight the research being done at IQC and the people doing the research. These stories serve to highlight the breadth and depth of the research produced at the Institute and the motivations that drive our researchers.

WHAT COMES AFTER QUANTUM?

Based on research published in Physical Review A on March 10, 2022
https://journals.aps.org/pra/abstract/10.1103/PhysRevA.105.032204

Quantum theory, the physics of the very small, helps us to understand nature and our world by explaining and predicting the behaviour of atoms and molecules. Researchers at IQC are interested in what comes after quantum theory, specifically the possibility of a broader theory that replaces quantum theory as a more complete description of nature.

In 1900, while studying radiation, Max Planck observed that energy could behave in a way not consistent with classical physics. Twenty years later a more fulsome understanding of matter emerged. Based on the research of physicists like Bohr, Schrödinger, and Heisenberg this new theory, quantum theory, accounted for the unpredictable nature Planck observed two decades before. In the same way that quantum physics built on our understanding of classical physics, a novel, post-quantum theory may build off our current understanding of quantum physics.

As a master's student with IQC and the Department of Physics and Astronomy, Michael Grabowecky was interested in exploring any potential deviations from quantum theory and identifying restrictions on any new potential theories.

To test quantum theory against possible alternates, a neutral or theory agnostic approach was needed. This approach allows data to inform an interpretation theory. The team designed an experiment to collect a large amount of data from a three-level system, then work out a theory directly from the obtained data.

"We do not assume any particular theory to be true before conducting the experiment. We want to make as little assumptions as possible, and we definitely don't want to assume that quantum mechanics is true," said Grabowecky. "The whole purpose of these kind of experiments is to let the statistics and the photons speak for themselves."

To minimize the experimental assumptions and take a theory-agnostic approach, the team used the framework of generalized probabilistic theories (GPTs). GPTs are operational theories in which classical and quantum physics are special cases. The team used GPTs because they require minimal assumptions and can be used to avoid any inherent quantum biases when conducting an experiment.

A digital computer stores and processes information using bits, which can either be 0 or 1. A quantum bit or qubit, can be both 0 and 1 and is a two-level system. In this experiment the team investigated a three-level system, where the bits have three degrees of freedom rather than two. The quantum analog of a three-level system is called a qutrit.

"We prepared a three-level system in a wide variety of ways and on each of those preparations, we performed a large number of measurements. The statistics associated with these random preparations and measurements were used to construct a physical theory describing our system," said Grabowecky.

The experiment found that quantum theory works well in describing the obtained data, but a broader theory beyond quantum may be possible. Furthermore, this research identified quantitative boundaries on the scope of possible deviations from quantum theory for three-level systems.

Grabowecky, now the Quantum Technology Lab Coordinator at IQC, is excited by the potential of this research. "Quantum theory does a great job at describing our three-level system and the world around us, but there is potential for other theories to fit in. This research gives us room to find other theories that may explain some phenomenon a little better than quantum theory."

The experimental data sets from this research can be used to test future theories that may supersede quantum theory and advance fundamental research.

This research was supported in part by the Canada First Research Excellence Fund (CFREF).

PHOTON DETECTOR MODULE GEARING UP FOR INTERNATIONAL SPACE STATION

Based on research published jpl.nasa.gov on March 7, 2022
https://www.jpl.nasa.gov/news/space-station-to-host-self-healing-quantum-communications-tech-demo

A single-photon detector and counting module (SPODECT) recently built by Waterloo's Quantum Photonics Lab for the International Space Station (ISS) will be used to verify quantum entanglement and test its survivability in space as part of the *Space Entanglement and Annealing QUantum Experiment (SEAQUE)* mission, in a collaboration with researchers at the University of Illinois Urbana-Champaign, the Jet Propulsion Laboratory, ADVR Inc, and the National University of Singapore

Waterloo's SPODECT module is unique in that it will include four single-photon detectors, multi-channel coincidence detection as well as a microcontroller for operation and photon counting, all in a very compact format. The Waterloo project is headed by faculty member Thomas Jennewein at IQC and the Department of Physics and Astronomy, and is led by research associate Joanna Krynski. The work is a partnership of the Quantum Photonics Lab (QPL) with Excelitas Inc. (Canada) who provided the Silicon-APD devices, and Dotfast Consulting (Austria) who provided the internal coincidence detection solution.

Serving as a continuation of the Cool Annealing Payload Satellite (CAPSat) project that intended to perform in-orbit measurements and annealing of silicon single-photon detectors, SEAQUE is the first ever space-based quantum experiment that integrates a source of entangled photon pairs using an optical waveguide crystal, which offers a higher photon pair production efficiency than regular bulk crystals. SEAQUE's pioneering design will also use a bright laser to repeatedly heal damage resulting from radiation exposure in between rounds of detecting photons generated from the entanglement source. This process, known as optical annealing, will help mitigate the increase of radiation-induced detector noise without the method of extreme cooling as used previously.

"This new detector module design is a step towards building a quantum communication technology at lower cost and lower complexity systems than conventional designs," said Krynski. "Our experiment will determine the viability of this new approach and whether it can be useful for future quantum information satellite networks."

"The SEAQUE mission will demonstrate a novel and efficient photon pair source, and a custom single-photon detector system, which could be a part of future quantum entanglement network nodes in space," said Jennewein. "The main benefit of space-based entanglement distribution will be that it enables quantum networking at much greater distances than purely ground-based architecture, as the space borne signals avoid the limitations of obstacles or absorptive media."

One of the most exciting challenges for this project was to fit all the required hardware for the SEAQUE system into the specifications laid out by commercial partner Nanoracks — a box that is only 30 cm by 20 cm by 10 cm — of which Waterloo's detector module SPODECT can only occupy a small fraction. Additionally, the chosen components must survive the turbulent launch, extreme temperature limits and exposure to space radiation.

SEAQUE is planned to launch early next year on NG-19, arriving at the ISS to reside in the Bishop Airlock. View the recording of CAPSAT's launch from October 2021.

The Waterloo team acknowledges funding support by the Canadian Space Agency (FAST program).

EXPLORING THE COMPLEXITY OF THERMAL PROPERTIES

Based on research published in Nature Physics on October 6, 2022
https://www.nature.com/articles/s41567-022-01742-5

Computational complexity is a field of computer science that aims to understand the resources needed to solve computational problems. Researchers Anirban Chowdhury and David Gosset at IQC have been collaborating with IBM researchers Sergey Bravyi and Pawel Wocjan to explore the exciting interface between computational complexity and quantum many-body physics.

They have been studying the computational complexity of approximating a quantity known as the quantum partition function. This quantity holds all the information about variables like energy and magnetization for any specific set of quantum particles interacting with its surrounding environment without any transfer of heat, a state known as thermal equilibrium.

"Partition functions are sort of like a master key for thermal equilibrium properties," says Chowdhury, a postdoctoral fellow at IQC and the Department of Combinatorics and Optimization at Waterloo. "Once you know the partition function, you know, or can calculate in a small number of steps, almost everything else about the system."

The problem of exactly computing the partition function is already understood to be extraordinarily hard. Therefore, the focus of Chowdhury and Gosset's latest research was to understand whether the problem is easier if one only asks for a good approximation.

"In computer science, if you want to understand how difficult a problem is, first you show that it's equivalent to some other problem that's better understood," says Gosset, faculty member at IQC and Waterloo's Department of Combinatorics and Optimization. "We have found that the partition function approximation is equivalent in complexity to several other problems, which can be called approximate counting problems, where the goal is to approximately count some quantum mechanical quantity."

By establishing an equivalence between these computational problems, Gosset and Chowdhury are building up an understanding of not only the partition function approximation algorithms, but also of this entire class of complex problems.

Another finding of their research was showing a new efficient approximation algorithm for computing the quantum partition function for a specific subset of cases known as dense local Hamiltonians, a case where every particle interacts with almost every other. Finally, the researchers also made improvements to existing classical and quantum algorithms for the partition function of general locally interacting quantum systems. Although these algorithms have an exponential runtime in the worst case, it is nevertheless of interest to decrease the resource requirements to improve their performance.

“Our hope is that other researchers can use the progress we made in this research and build upon it,” says Chowdhury. “Then, we might be able to precisely understand the computational complexity class that characterizes the difficulty of the partition function approximation problem.”

The paper was published by Chowdhury and Gosset from IQC along with their collaborators Sergey Bravyi and Pawel Wocjan from IBM Thomas J. Watson Research Center. This research was funded by a grant from the Army Research Office.

RESEARCHERS FIND SIMPLE METHOD FOR CREATING 3-DIMENSIONAL BRIDGE STRUCTURES ON MICROCHIPS

Based on research published in Applied Physics Letters August 29, 2022
https://pubs.aip.org/aip/apl/article/121/9/094001/2834098/Aluminum-air-bridges-for-superconducting-quantum

Researchers at the IQC have found a new one-step process to construct tiny bridge structures on microchips with superconducting circuits, which are essential for future quantum computers based on superconductors.

Currently, superconducting circuits are believed to be one of the most promising candidates for information storage on future quantum computers. These superconducting circuits may have the processing ability to make efficient breakthroughs in complex problems – such as pharmaceutical drug design – that are too time consuming to be computed on today’s computer systems.

These tiny bridge structures, known as air bridges, are used to create complex designs, as they enable circuit crossings and mitigate loss of information in superconducting circuits on microchips.

“Our new method creates robust air bridges with a single lithography patterning step,” said Noah Janzen, a PhD student at IQC and the Department of Physics and Astronomy, and lead author of this study. “By using a single step process, the time, cost, and amount of materials needed to create these structures is significantly reduced and optimized compared to previously known air bridge fabrication processes.”

The air bridges are miniscule, with a width of 6 μm, over 10 times smaller than a strand of hair, and a length ranging from 20 – 100 μm (at their largest, the size of a single hair). These bridges improve the quality of microchip devices by reducing quantum level deterioration effects, known as quantum decoherence, of the superconducting currents.

To create the air bridges, the research team layered a polymer on top of the microchip, then created a 3-dimensional template for the bridge by etching the template into the polymer layer using a focused beam of electrons through a process called electron beam lithography. A thin layer of aluminum was then deposited on top of the bridge template, and the polymer template was removed, leaving only the aluminum bridge suspended in the air. Support by staff at the Quantum-Nano Fabrication and Characterization Facility and the quality of the infrastructure at this facility have been essential for this development.

Air bridges are one important ingredient for improving the quality of the superconducting chips, and they also open up the design space on these chips from 2-dimensions to 3-dimensions. Combined with the newly reported simple method for creating air bridges, this provides researchers with a process to create more complex microchips and devices.

“This new method has already enabled us to develop a new device for the exploration of fundamental topics in quantum information. We expect it will be useful in a broad range of efforts in the field,” said Adrian Lupascu, IQC faculty member and professor of Physics and Astronomy at Waterloo.

The paper was selected as an Editor’s Pick.

SUBATOMIC MRI COULD LEAD TO NEW DRUG THERAPIES

Based on research published in Proceedings of the National Academy of Sciences of the United States of America on September 26, 2022
https://www.pnas.org/doi/abs/10.1073/pnas.2209213119

A new imaging technique using quantum science may lead to novel drug therapies and treatment options, a recent study has found.

Researchers at Waterloo and supported by Transformative Quantum Technologies have demonstrated the feasibility of Nuclear Magnetic Resonance diffraction (NMRd) to investigate the lattice structure of crystalline solids on an atomic scale, a feat that had only been possible for larger-scale imaging applications like Magnetic Resonance Imaging (MRI).

“NMRd was proposed in 1973 as a method to study the structure of materials,” said Dr. Holger Haas, one of the lead authors of the study and alumnus of IQC, now at IBM. “At the time, the authors discarded their idea as ludicrous. Our work comes tantalizingly close to realizing this crazy idea of theirs — we have shown that it is possible to study structures on an atomic length scale over sample volumes that are relevant for many biological and physical systems.

“NMRd opens up a tremendous variety of capabilities in many research directions, including studying both nanocrystals and organic compounds,” added Haas. The ability to image biological structures, like protein molecules and virus particles, on the atomic scale can advance the understanding of their function and potentially lead to new drug therapies and treatment options.

NMRd works by exploiting a property in nuclei called spin, a fundamental unit of magnetism. When placed in a magnetic field, the nuclei essentially act as magnets due to this spin. A time-varying magnetic field can perturb the spins, changing the angle of the spin – in technical terms, this is called encoding a phase in each spin. At a particular encoding time, all spins will point back to the initial direction. When this occurs, a diffraction echo is observed, a signal that can be measured to find the lattice constant and shape of the sample. Each nucleus will produce a unique signal, which can be used to discern the structure of the molecule.

The challenge in achieving atomic-scale NMR was the difficulty of encoding large relative phase differences between neighbouring nuclear spins on the atomic scale, meaning that a diffraction echo could not be observed. The researchers overcame this limitation by using quantum control techniques and generating large, time-dependent magnetic field gradients. With this, they could encode and detect the atomic scale modulation in an ensemble of two million spins and measure the displacement of the spin ensemble in a sample with subatomic precision.

This research represents substantial progress in establishing atomic-scale NMR as a tool for studying material structure.

Sahand Tabatabaei, co-lead of the study and PhD student at IQC and Waterloo’s Department of Physics and Astronomy, adds, “now that we are close to being able to do NMRd on a lattice at the atomic length scale, we can also really start studying more fundamental quantum physics, like quantum transport phenomena and quantum many-body physics, at the atomic length scale, which hasn’t been done before on samples of this size.”

The study was co-authored by Haas, Tabatabaei, Dr. William Rose, Dr. Pardis Sahafi, Dr. Michèle Piscitelli, Andrew Jordan, Pritam Priyadarsi, Namanish Singh, Dr. Ben Yager, Dr. Philip J. Poole, Dr. Dan Dalacu, and Dr. Raffi Budakian.

This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund.

USING DISORDER TO FIND NEW MAGNETIC TRANSITION PATHWAYS

Based on research published in Physical Review B on September 29, 2022
https://journals.aps.org/prb/abstract/10.1103/PhysRevB.106.094435

A team of researchers at IQC have found a new tunable pathway to manipulate nanoscale magnetic structures known as skyrmions.

Their results advance efforts to access different configurations of these structures and increase their stability for magnetic memory applications, such as using these structures as new types of bits in classical or quantum computers.

Skyrmions are tiny structures present in some magnetic crystals, formed by the collective alignment of magnetic moments from individual atoms into a twisting vortex significantly larger than atomic scales. These vortices create 3-dimensional tube magnetic structures, similar to nanoscale tornadoes, that gather into triangular or square lattice patterns of multiple vortices. The skyrmions and lattice patterns can be measured and controlled by external magnetic fields or currents.

"Previously, a lot of research has been devoted towards skyrmions in really pure, ideal single crystal systems," says Melissa Henderson, a PhD student at IQC and the Department of Physics and Astronomy at Waterloo. "It's been a commonly held belief that the total number of skyrmions in a sample, also known as the topological charge, is conserved during rearrangements. We discovered that this conservation of skyrmion number is not the case in crystals with substantial crystalline and chemical disorder, which leads to some really interesting properties and phenomena."

The team, which includes collaborators from McMaster University and the National Institute of Standards and Technology (NIST), introduced disorder into their crystalline material by growing a site-disordered material which exhibits variations in atomic site occupancies, randomly incorporating cobalt manganese or zinc atoms into the repeating crystal pattern. This disorder interrupts the usually straight skyrmions to create a labyrinth of zig-zag patterns that merge, end, or separate in the crystal.

Using heat and rotating the magnetic field, alongside small angle neutron scattering measurements, the researchers heated up the sample to create the disordered skyrmions. In some experiments, the researchers then took the samples and rotated them in the magnetic field to reorient the skyrmions into an ordered triangle lattice pattern. Starting from either these ordered or disordered states, the researchers began to cool the material.

"As you cool it past a certain point, you'll exit the thermal equilibrium phase and go into a metastable phase, with the degree of skyrmion order in this phase dependent on the amount of order in the initial thermal equilibrium phase," says Henderson. "Then as you keep cooling further, the exchange parameters will change more substantially, altering the ratios, magnitudes, and directions of the interactions. This will mediate a transition to a square lattice arrangement, so you go from a triangular to a square pattern.

"It was previously thought that in disordered samples, the disorder may inhibit the transition from triangular to square. That is why what we observed is surprising. We observed a disordered-to-ordered transition where we actually gain order when coming from the disordered triangular state to the square state. This is only possible by changing the topology of the system."

To date, this skyrmion lattice transition has only been observed for conversions between ordered triangular to ordered square lattices in bulk systems. The researchers discovered an additional transition pathway between disordered triangular states to ordered square states that must undergo a change in the number of skyrmions present, upturning the previous belief that the number of skyrmions should stay constant during phase transitions.

Throughout the metastable phase, the researchers have shown additional disorder-induced effects where the skyrmions persist in a memory effect. The skyrmions are annihilated and then recovered in the metastable phase, thought to change between structures known as magnetic torons – tiny skyrmion filaments that maintain the topological charge of the skyrmion.

"Transition between ordered and disordered states has always fascinated people in general and physicists in particular. What are the pathways that lead one into another?" says , faculty member at IQC and Waterloo's Department of Physics and Astronomy. "Now we can study in situ such transitions where a quantum phase topology plays an important role and might help to advance spintronic devices."

NEW EXOTIC TWO-DIMENSIONAL MAGNET MAY HOLD PROMISE FOR QUANTUM COMPUTING

Based on research published in Nature Materials on November 17, 2022
https://www.nature.com/articles/s41563-022-01401-3

At the forefront of condensed matter physics, materials with novel quantum mechanical properties are being investigated for fundamental science and potential applications in quantum technology. Dr. Adam Wei Tsen, a faculty member at IQC and the Department of Chemistry at Waterloo, along with his team, are diving into this field with a particular focus on two-dimensional (2D) quantum materials.

The team is exploring how the magnetic properties of the layered material alpha ruthenium chloride (α-$RuCl_3$) change in samples that approach the atomically thin 2D limit. At the atomic level, each electron has a quantity called spin, which gives rise to varying magnetic properties based on how the neighbouring spins interact. These interactions can also differ significantly between a single layer material and the bulk 3-

dimensional sample of the same material consisting of many stacked layers. Tsen's team is the first to study the magnetic properties of α-$RuCl_3$ in its single layer form.

In its bulk form, α-$RuCl_3$ hosts a unique interaction between neighboring spins, called the Kitaev interaction, named after Russian-American physicist Alexei Kitaev. Kitaev's work mathematically proved that when this is the only magnetic interaction in a 2D material with a honeycomb-shaped structure, the spins are entangled and exist in a liquid-like state, even at extremely low temperatures. If researchers can find a 2D material where the Kitaev interaction is more significant than all other spin interactions, it may lead to future applications in quantum information processing.

Unlike in theoretical predictions, in real materials the Kitaev interaction always competes with other ordinary spin interactions, and so careful tuning is required to engineer the magnetic properties. Tsen's team studied how different sample thicknesses impact the magnetic properties of α-$RuCl_3$.

"As α-$RuCl_3$ has a layered honeycomb structure, we can isolate a single atomic layer of these materials with relative ease," says Tsen. "That allows us to study this quantum material in a form that is closer to the model system proposed by Kitaev."

In these experiments, IQC researcher Dr. Bowen Yang, a postdoctoral fellow supervised by Tsen, used a nanoscale device geometry borrowed from spintronics (spin-based electronics), called the magnetic tunnel junction, which is used in today's memory storage technology. In this device, thin layers of α-$RuCl_3$ were isolated and sandwiched between two conducting materials. By examining how electrons tunneled through the insulating α-$RuCl_3$, Yang was able to directly measure the material's spin wave excitations down to the monolayer. The researchers found that, in contrast to the bulk crystal, the magnetic field needed to polarize the spins in the 2D sample was smaller in the direction perpendicular to the hexagonal layer structure than in plane with it.

The team's collaborators from the University of Michigan then carefully examined the structure of monolayer α-$RuCl_3$ using a technique called electron diffraction and found that it exhibited several distortions relative to the bulk crystal. Theorists from Goethe University Frankfurt and Wake Forest University then calculated the magnetic interactions from this distorted structure. They successfully explained the change in the effect of the magnetic field, and further discovered that the Kitaev interaction was substantially increased. Collectively, these findings highlight the importance of dimensionality in tuning the properties of magnetic materials and demonstrate that monolayer α-$RuCl_3$ may be more relevant for quantum computing applications than its bulk counterpart.

At the same time, a perpendicular magnetic field has been theoretically predicted to induce spin liquid phases even when the system was not a spin liquid to begin with. "What's known about the bulk crystal is that you have to apply an extremely large magnetic field of about 35 Tesla to drive it out of its ground state, which is largely inaccessible by most groups," says Tsen. "But it only takes about 6 Tesla, a much smaller magnetic field, to break this ground state for a single layer, which could be very promising for the future".

The paper was published by Yang, Dr. Fangchu Chen, Tsen and their collaborators. Yang recently won the IQC achievement award for this work. The research was funded in part by the US Army Research Office as well as Transformative Quantum Technologies (TQT) at the University of Waterloo.

NEW QUANTUM TOOL DEVELOPED IN GROUNDBREAKING EXPERIMENTAL ACHIEVEMENT

Based on research published in Science Advances on November 18, 2022
https://www.science.org/doi/10.1126/sciadv.add2002

For the first time in experimental history, researchers at IQC have created a device that generates twisted neutrons with well-defined orbital angular momentum. Previously considered an impossibility, this groundbreaking scientific accomplishment provides a brand-new avenue for researchers to study the development of next-generation quantum materials with applications ranging from quantum computing to identifying and solving new problems in fundamental physics.

"Neutrons are a powerful probe for the characterization of emerging quantum materials because they have several unique features," said Dr. Dusan Sarenac, research associate with IQC and technical lead, Transformative Quantum Technologies at Waterloo. "They have nanometer-sized wavelengths, electrical neutrality, and a relatively large mass. These features mean neutrons can pass through materials that X-rays and light cannot."

This new research, from Dr. Dmitry Pushin's research group at IQC, created devices with microscopic fork-like silicon grating structures. When a beam of single neutrons passed through this device, the individual neutrons began winding in a corkscrew pattern, indicating that quantized orbital angular momentum had been generated in these neutron beams. Devices were created at Waterloo's QNFCF.

This project is supported in part by the Canada First Research Excellence Fund through the TQT program.

INVESTIGATING THE IMPACT OF A LASER'S NOISE PROPERTY ON QUBITS

Based on research published in npj Quantum Information on June 27, 2022
https://www.nature.com/articles/s41534-022-00586-4

When IQC Research Associate Dr. Matthew Day had his lab temporarily closed during the COVID-19 pandemic, the experimentalist found himself at some loose ends. What's an experimentalist to do without his equipment? For Day, it was a chance for him to ask questions he'd been thinking about for a while. Specifically, Day wanted to know: how does equipment in the lab affect experiments?

Day set out to examine how the noise property of a laser affected the control of qubits in Dr. Crystal Senko's ion trapping lab. Alongside several researchers, Day studied the unique structure of laser noise and developed an algorithm that determines when a stabilised laser source has been optimised for quantum control of atomic qubits. Noise in a laser refers to the random fluctuations of a laser's light.

"If you reduce the influence laser noise, does it mean you don't have to worry about the laser affecting your work?" Day said. "Is it possible? The answer is yes."

Day, trained as theorist in school, has created a tool with his collaborators to measure when a laser is inconsequential in an experiment. It's a new metric he noted, as most researchers focus on the linewidth of their lasers and its effect on experiments. This algorithm, however, lets individuals know about the quality of the laser they are using.

"Do you need to buy a better or different laser for your experiment?" Day said. "This tool will let you know if you should. Laser companies and academics are going to find this interesting."

Day has tested the algorithm in the lab, but he senses that the tool will also be useful for quantum researchers who use microwave sources as well.

"People know that it's been a problem," Day said. "But not one has taken the time to do anything about it." He's grateful that the downtime caused by the COVID-19 pandemic let him focus his energy on this question, because he believes it will help him create better experimental outcomes in the lab.

"Limits are being reached in our labs and testing the capacity of our equipment," he notes. "We need to understand these limiting errors and need to understand how equipment quality is affecting these errors."

While Day originally envisioned himself working as a theorist in quantum gravity, he discovered during his schooling that he liked making useful research contributions related to laser-affected qubits. Researchers, experimentalists or theorists, need to understand both sides of their research, and this is something Day practices through his research. IQC's collaborative environment is reminiscent of his experience at the University of Bristol where he earned his PhD and experienced that collaborative way of research for the first time.

Day believes that this type of research can help understand how important it is to take into consideration the design of lasers to ensure that they are useful for experiments. Today, Day has already pulled his focus back to the lab where he is currently researching miniaturised laser sources using integrated photonic circuits in ultrawide bandgap materials. However, he hopes that other researchers pick up his tool and continue to test his theories in new environments like a 2-qubit gate. He's created a template for how to do it, and for Day, the exciting aspect of quantum research is to help motivate fellow researchers to attain the next level of their work.

This project is supported in part by the Canada First Research Excellence Fund through the TQT program.

NEW LIGHT ABSORBING MATERIAL TO IMPROVE CANCER DOSE MONITORING AND EYE IMAGING

Based on research published in Scientific Reports on June 11, 2022
https://www.nature.com/articles/s41598-022-13537-y

The creation of a material that absorbs the majority, if not all light, would improve the effectiveness of health-related equipment. Dr. Michael Reimer, a faculty member at IQC and researcher in Electrical and Computer Engineering at the University of Waterloo, has set his sights on creating an artificially engineered material, known as a metamaterial, to do just that. Reimer and his research team have achieved this goal and developed a new class of materials that absorbs light better than anything that has existed to-date.

“This new research discovery will have significant implications for wavelengths used in dose monitoring for cancer treatments, telecommunications, defence and optical coherence tomography to detect blinding diseases sooner,” said Reimer.

Reimer’s team includes postdoctoral fellow Dr. Sasan V. Grayli; PhD students Brad van Kasteren, who developed the numerical calculation and design, and Burak Tekcan, who worked in the Quantum Nano Fabrication and Characterization Facility at Waterloo to realize the nanowires as close as possible to the shape of the nanostructures used in modeling; and a collaboration with Dr. Zbig Wasilewski from the Department of Electrical and Computer Engineering, who grew the high-quality semiconductor material used to fabricate the nanowires. Together, they made a new class of material that is able to absorb over 99% of light. By carefully designing the shape of the nanowires and the spacing between them, the team demonstrated the ability of the metamaterial to absorb light over a broadband range of wavelengths.

“We showed a very good agreement between the theory that we have developed to explain the absorption characteristics of the nanowire array and the experimental work. It’s remarkable that we were able to measure 93% absorption efficiency over an unprecedented spectral range, from 900 nm to 1650 nm,” said Grayli.

Now that Reimer has this new material, the next step is to incorporate it into devices. The first device his team is trying to realize is a detector capable of measuring single particle of light, also known as photons. In the longer term, he is trying to make a single photon-sensitive camera for eye imaging.

“What’s nice about all these detectors – like the single photon detector — is that in the short-wave infrared region, existing portable single photon detectors based on semiconductors have a limited efficiency of 25%. Since we can absorb over 90% of the light, it will significantly improve the efficiency of the detectors for the related applications," said Reimer.

In the context of eye health, currently, if high efficiency monitoring and detection is desired for the area outside of what your eye can see, superconducting nanowire detectors that transport electrical charges without resistance at the nanoscale are required. The portability and usability of these detectors has always been a limitation of their use given they need to be cooled to three kelvin. Conversely, semiconductor technology including what Reimer is working on with his team is portable, and with this project they are developing a new semiconductor photodetector with higher efficiency than all other semiconductor-based detector technologies to date. Previous silicon and alloy-based photodetectors used for eye imaging have a limited efficiency at wavelengths of light between 800 nm and 1000 nm, also known as the valley of death. The creation of this new material that provides higher absorption will have benefits in the kind of applications that are working in the wavelength range of 900 nm - 1650 nm.

For this experiment, the researchers used a broadband light source to illuminate the fabricated metamaterial and measured the amount of light that was reflected by it and transmitted through it. This allowed them to deduce how much light was absorbed by the material. The nanowires typically act as waveguides to direct the light, but with careful arrangement of the nanowires in an array, the portion of the light that is not trapped in the individual nanowire can be collected by the neighbouring nanowires, leading to over 90% absorption of the incident light. Much effort has gone into tailoring the shape for the nanowires so that they no longer act like a bulk material that reflects a significant amount of light, and instead creates a mechanism for improved light absorption due to their spacing.

With the development of this new material, which promises more light absorption, Reimer believes there will be large-scale healthcare and telecommunications implications. Returning to the research, Reimer is now directing his attention to the surface of the nanowires to avoid unwanted false signals on the detector to reach the single photon level. He is looking into ways to treat the surface to lessen the amount of material noise while maintaining the high absorption characteristics of the metamaterial in the desired wavelength range. For now, they're one step closer to higher efficiency technology that will help with detecting early signs of blindness and calibrating medicinal dosages for cancer patients.

This research was supported in part by the Canada First Research Excellence Fund.

MAKING FUTURE QUANTUM COMPUTERS LESS SUSCEPTIBLE TO ERRORS

Based on research published in PRX Quantum on August 1, 2022
https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.3.030322
Alongside research

What happens when a computer makes a 'typo' or error at the very fundamental level – if a zero accidentally becomes a one? In classical computers, we can use repetition in the binary signals to make computers tolerant to faults such as these.

This same repetition process, however, cannot be applied to quantum computers due to the fundamental principles of quantum mechanics. The same property that promises to make quantum communications secure – the fact that quantum particles cannot be measured or copied without being corrupted – also makes future quantum computers more prone to errors and makes errors on future quantum computers harder to detect and fix.

During his PhD at IQC, Dr. Theerapat Tansuwannont, now an alumnus, worked with Dr. Debbie Leung, faculty member at IQC and Waterloo's Department of Combinatorics and Optimization, to develop new techniques for quantum error correction without introducing new errors to the original encoded qubits.

"To correct errors, we use extra qubits called ancillas to collect information about the quantum errors without measuring the original encoded qubits. But if a data qubit or an ancilla has an error, it's a bit like disease, you can potentially spread the error to multiple qubits or ancillas," says Leung. "Therefore, we are trying to find new methods to correct errors and compute without spreading errors, a property called fault tolerance. Traditionally, this requires a lot of ancillas, and our main goal is to reduce the number of ancillas for fault tolerance."

Since quantum computers are still a future goal, theorists studying error correction methods are working on a wide variety of approaches to ensure that error correction methods, known as error-correcting codes, are available to suit the specific demands and limitations of future quantum hardware.

In their latest paper, Tansuwannont and Leung unified several existing error correcting methods to create a new technique that used fewer ancillas overall. They combined a method known as flag error correction, which identifies faults in the ancillas using secondary ancillas, with a method known as weight parity error correction, combining errors that have the same overall impact together and correcting them in the same way, even if the errors themselves are very different.

This combination led to a new family of codes, called capped colour codes and recursive colour codes, which is an extension of previous "colour codes." The addition of the cap allows researchers to apply the flag and weight parity methods into this code set.

"The recursive capped colour codes use half as many qubits as the colour codes with similar fault tolerant properties do," says Tansuwannont. "The lower number is meaningful because it is closer to the number of qubits experimentalists are able to make and work with today."

Overall, the work of Tansuwannont and Leung develops a number of new code sets and circuits that lead to a set of fault tolerant protocols for quantum error correction. Their research demonstrates that the overall amount of computational resources and the cost needed to achieve this can be significantly reduced. Their efforts have brought researchers closer to bridging the gap between theoretical and experimental work, and towards a future quantum computer.

"From a theoretical perspective, we want to design a protocol that has a high threshold for correcting errors. From the experimentalist's point of view, they want to develop hardware that has low error rates," says Tansuwannont. "Once qubit technology gets to a point where the physical error rate is below the threshold for our error correction methods, then we hope that a quantum computer can be built."

NEW DISCOVERY MAY BE KEY TO CONTROLLING CHEMICAL REACTIONS

Based on research published in Nature on February 1, 2023
https://www.nature.com/articles/s41586-022-05635-8#Ack1

Unexpected resonance frequencies observed in reactions between two molecules

A new study published today in Nature is changing our understanding of chemical reactions and overturning previous theoretical models by finding an unexpected resonance frequency during the reaction of two molecules.

Resonance is when one object vibrating at the same natural frequency as a second object forces that second object into vibrational motion.

This ground-breaking finding is the first time a resonance has been observed between two ultracold molecules and is a stepping-stone for researchers to learn about and control the molecules that comprise our universe.

"Resonances occur when vibrations at a specific frequency get preferentially amplified. For example, when a piano string gets hit by the hammer, it vibrates at a specific frequency based on the length and thickness, creating a musical note unique to that string," said Dr. Alan Jamison from IQC and the Department of Physics and Astronomy at Waterloo. "Similar resonances occur in atoms, where very specific frequencies of energy create stronger than expected responses in the chemical systems."

Previously predicted to be an impossibility, Jamison and his collaborators from the Massachusetts Institute for Technology (MIT) were able to observe resonant frequencies in a chemical reaction between two ultracold molecules. By cooling down sodium-lithium molecules to near-absolute zero temperatures, the team could control the reactions at a quantum level. Without such control, the unusual resonance would never have been noticed.

IQC RESEARCHERS BRING THEORY TO REALITY WITH A NEW EXPERIMENT

Based on research published in Physical Letters Review on March 13, 2023
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.110801

Energy is present everywhere in the universe, from the tiniest particles to the vastness of space. According to quantum mechanics, vacuum states like outer space are not actually empty, because when observed at microscopic scales, there are spontaneous energy fluctuations. These can be loosely interpreted as a sea of particles 'popping in and out of existence' for short times, and results in regions of positive and negative energy densities. Overall, these fluctuations keep the vacuum in its lowest possible energy state, known as the zero-point energy.

However, it has been theorized that under very specific conditions, quantum information processing and quantum thermodynamics tools might be useful for localized energy extraction from the zero-point energy of a quantum vacuum. Researchers at IQC have implemented the first experiment in which quantum entanglement is used as a resource to activate the vacuum zero-point energy.

The team included Dr. Raymond Laflamme, IQC faculty member and professor in Waterloo's Department of Physics and Astronomy, and Dr. Eduardo Martín-Martínez, IQC associate and professor in the Department of Applied Math, as well as Dr. Nayeli Rodríguez-Briones and Dr. Hemant Katiyar, both recent graduates from IQC and the Department of Physics and Astronomy, now working at University of California, Berkeley and IonQ Canada, respectively. Together, they experimentally tested the impact of entanglement between particles to extract energy from a vacuum state.

The concept of local extraction of zero-point energy was first proposed by Masahiro Hotta in 2008, who conceived the protocols named quantum energy teleportation. In this protocol, energy is not being moved or transported between the two locations. Instead, energy is spent in one location of the system to gather information. This information is then shared via entanglement and used at the second location to extract energy. This protocol had remained theoretical until now, as the team of IQC researchers has published the first experiment to test quantum energy teleportation.

"When you start focusing on local sections of the vacuum, you're going to see fluctuations of energy. Sometimes, you're going to have fluctuations that give you energy, and sometimes they take energy, but on average, you're always going to be inputting energy into the system," says Martín-Martínez. "But when the vacuum has entanglement — which is the case for most systems in the world — you can spend energy to get information about one local state. Then, you can send that information to somebody with access to a different part of the vacuum. From there, they can use that information to catch the right fluctuation in their local state to extract energy."

In this experiment, the researchers used nuclear magnetic resonance (NMR) to simulate the quantum system of a vacuum using three carbon atoms in the molecule transcrotonic acid. The carbon nuclei each have an inherent spin state of either up or down, which can be harnessed as a qubit in NMR experiments. Two carbon nuclei (A and B) act as the entangled locations, and the third carbon nucleus acts as an auxiliary qubit. To perform the experiment, the auxiliary qubit was used to measure qubit A without transferring any energy between qubits A and B. The information gained from this measurement was then used to extract energy from qubit B without transferring energy between the qubits. This process demonstrated the feasibility of extracting energy in a strong local passive state using the quantum energy teleportation protocol.

"Our work gives insight into the interplay between entanglement and locality, and the effect it has on the energy flows in the system," says Rodríguez-Briones. "Our research connects concepts from several fields, such as quantum information and quantum thermodynamics, which could potentially be useful for other theoretical physics problems and applications."

While this experiment is the first step, this theory has implications in a wide range of quantum applications and our understanding of quantum theory. For example, understanding quantum energy teleportation protocols may give insights into the black hole information paradox and may lead to applications using quantum thermodynamics to improve quantum devices.

"By doing an experiment, even if it's a very simple first step in using theoretical ideas and concepts from quantum theory, we can prove that the world really behaves in alignment with the theoretical principles of quantum mechanics," says Laflamme. "Our experiment shows that extracting energy from an entangled ground state is possible. It's a small step, but it opens the door for many other things – quantum information science is becoming quantum information technologies."

MITIGATING ERRORS IN SUPERCONDUCTING QUANTUM CIRCUITS TO PAVE THE WAY FOR FUTURE QUANTUM COMPUTERS

Based on research published in Physical Review Applied on September 6, 2022
https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.18.034009

With the quantum age on the horizon, scientists are working to develop quantum computers that will have a processing speed exponentially faster than today's most advanced supercomputer. Building a useful quantum computer is one of the great engineering challenges of our time. In all implementations, qubits that are reliable, stable, and scalable are essential in this endeavor.

The accuracy and reliability of qubits is being investigated by a group of researchers lead by Dr. Matteo Mariantoni, a faculty member at IQC and professor in the at Waterloo. The research team is working with superconducting quantum circuits, which are currently among the leading platforms in efforts to develop a quantum computer.

Using chips comprised of aluminum layers on top of silicon wafers, the group is creating superconducting devices. As researchers build toward fully functional quantum computers with this technology, it is essential to understand and measure the amount of decoherence – the loss of quantum information due to loss or noise – in a circuit. These effects need to be remediated or minimized for any future quantum computer to function well and yield accurate results.

Superconducting circuits are affected by defects in the surrounding material called “two-level systems” (TLSs) which, much like qubits, can be in one of two distinct energy levels, either a ground state or an excited state, at any given moment. In a previous study conducted by the research group, they observed that thermal fluctuations between ground and excited states of TLSs cause qubit decoherence and necessitate constant recalibration of the qubit control parameters. In this continuation of their work, they have shifted their focus from qubits to resonators, another type of quantum object essential for quantum computing, in order to better understand the physics of TLS defects.

Dr. Jérémy Béjanin, a postdoctoral fellow at IQC, was part of the group investigating the fluctuations attributable to TLSs. “Since TLS defects cannot be directly measured, we use resonators as probes to indirectly detect the TLS fluctuations that cause decoherence.”

In the latest experiment, an electromagnetic field was applied to energize the TLS population, then the researchers used a resonator to observe the platform and identify how much of the energy was dampened by TLS defects in the circuit. “You can think of a resonator like a string on a guitar that vibrates at a particular frequency, only in this case it is not an acoustic vibration but an electromagnetic vibration,” says Béjanin. “In our experiments, the resonators are aluminum bands on the chip that resonate, or electromagnetically vibrate, at a specific frequency. We can measure the exact frequency of the resonator and observe how long it rings to determine the quality factor of the resonator.”

Quality factor is measured by how long the resonator will resonate, or vibrate, at one specific frequency. “TLS defects take energy away from resonators, they reduce the quality factor. You can think of them as putting your finger on the vibrating string of the guitar and muting the resonator, or shortening the length of the vibration,” says Béjanin. The researchers used a microwave signal that minimally interacts with the resonator to energize the TLS defects, which has been shown to suppress TLS errors at high power. This allows them to “remove” a fraction of the TLSs that affect the resonator, thereby allowing for a better characterization of the fluctuations. A weaker probe which interacts with the resonator directly is used to track its resonant frequency and infer the quality factor continuously.

This study is the first experiment to monitor resonator frequencies constantly over many days – up to five in this result. Their data shows explicitly that the TLS defects can skew experiments on both short and long-time scales. “Because these fluctuations change the performance of qubits and resonators over time in an unpredictable way, they make the results of computation inconsistent and unreliable,” explains Béjanin. “That is problematic for quantum computers.”

Quantum computers based on these superconducting platforms, including those at IBM and Google, are subject to TLS defects and their fluctuations. This research from Mariantoni’s group indicates that any computational system not constantly monitored and recalibrated to account for random fluctuations is likely to produce incorrect results without the user knowing. With this issue present, it will be difficult to make a high-quality quantum computer.

Having done the research to characterize this TLS problem, next, the team is planning to investigate ways to mitigate TLS errors. Understanding such dissipative phenomena as quantum decoherence will pave the way for scaling up future quantum computers.

This research was supported in part by the Canada First Research Excellence Fund.

Recruitment – Faculty

Alongside research and training, each year IQC prioritizes recruitment activities to continue to attract world-class theoretical and experimental researchers across a range of disciplines. With a talented cohort of 30 faculty members collaborating on some of the most complex problems in the history of science, IQC is dedicated to maintaining its strong research team.

IQC is actively engaging in faculty recruitment and is selective in bringing the best and the brightest through faculty and research associate hiring. Most recently, IQC hired Dr. Graeme Smith, who joined IQC in July 2023 and is a faculty member in Waterloo’s department of Physics and Astronomy. Smith’s research areas include quantum information and quantum computing. He comes to IQC from the University of Colorado at Boulder.

The cutting-edge research taking place at IQC in conjunction with the entrepreneurial spirit at the University of Waterloo means that IQC must not only compete against other academic institutions for world-class talent, but also against a rapidly growing private sector with a strong appetite for quantum talent, including startups built by our existing faculty.

In fiscal 2022-2023, Dr. Kyung Soo Choi departed IQC to run his startup, Q-Block Computing. The startup currently employs several staff in Waterloo Region and is adding to the vibrant entrepreneurial ecosystem.

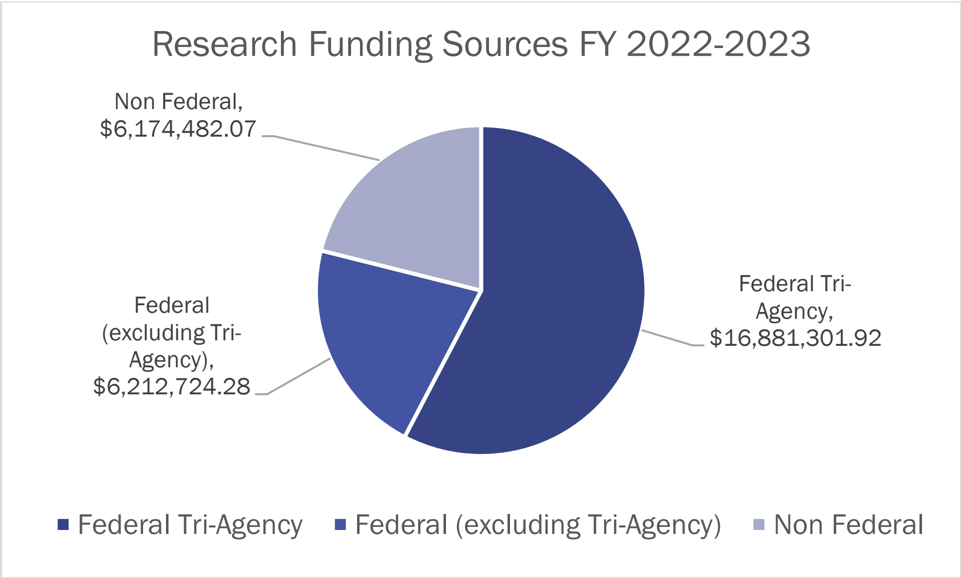
Additionally, former IQC faculty member and interim director Dr. John Watrous moved into the role of Technical Director, IBM Quantum Education after a successful sabbatical in the same role. Watrous is among a half dozen former IQC members that are driving the development of quantum computing at perhaps the world's most advanced active quantum computer.

Recruitment – Research Associates

Research associates make invaluable contributions to academic progress at IQC. Many of our research associates bring years of research experience to IQC and are integral to the operation of our most sophisticated laboratories and technical operations. In 2022-2023 IQC employed 22 research associates. Of these, five were newly recruited in 2022-2023 and include hires from Germany, Hong Kong and across Canada. Another new research associate is a former IQC graduate student, which is a testament to the excellent graduate programs IQC has developed over the last 20 years. These research associates work with IQC principal investigators to advance research programs and initiatives. Our research associates also participate fully in the commercialization of their unique expertise with three long-time research associates founding startups in 2022-2023. A full list of all IQC contributors in 2022-2023 including 30 faculty members, two research assistant professors, and 22 research associates can be found in Appendix C beginning on page 78.

Awards & Research Chairs

IQC researchers have collectively been awarded $29,268,508 in research funding during the period of April 1, 2022, to March 31, 2023. Funding sources are diverse and include research chair awards, funding from the Government of Canada, the Canada Foundation for Innovation (CFI), industry partners and others. It is worth noting that private sector funding reached almost $400,000 in 2022-2023 and the cumulative total for the current and previous agreements with ISED is just over $128M.



The research by IQC faculty members has a significant global impact, indicated by numerous prestigious awards and acknowledgements. These accolades reinforce IQC and Canada's exceptional standing in quantum information science. Here are some notable awards received by faculty members in 2022-2023:

Faculty Member	Award Sponsor
Adam Wei Tsen	CFREF (Canada First Research Excellence Fund)
	Gerald Schwartz & Heather Reisman Foundation, The
	Ministry of Colleges & Universities (MCU) (formerly MEDJCT) - ERA (Early Researcher Award)
	NSERC - Discovery Grants - Individual (RGPIN)
	NSERC - I2I (Idea to Innovation Program)
	US Army Research Office
Adrian Lupascu	DRDC (Defence Research and Development Canada)
	Gerald Schwartz & Heather Reisman Foundation, The
	NSERC - Discovery Grants - Individual (RGPIN)
Alan Jamison	DRDC (Defence Research and Development Canada)
	NSERC - Discovery Grants - Individual (RGPIN)

Ashwin Nayak	Fujitsu Laboratories of America Inc Mitacs Inc Mitacs Partner Contribution
Christine Muschik	Ministry of Colleges & Universities (MCU) (formerly MEDJCT) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN)
Christopher Wilson	CFI - IOF (Infrastructure Operating Fund) DRDC (Defence Research and Development Canada) Mitacs Inc Mitacs Partner Contribution NSERC - Discovery Grants - Individual (RGPIN)
Crystal Senko	CRC – NSERC Ministry of Colleges & Universities (MCU) (formerly MEDJCT) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN)
David Cory	CFREF (Canada First Research Excellence Fund) DRDC (Defence Research and Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
David Gosset	CIFAR (Canadian Institute for Advanced Research) IBM US NSERC - Discovery Grants - Individual (RGPIN)
Debbie Leung	NSERC - Discovery Grants - Individual (RGPIN)
Dmitry Pushin	NSERC - Discovery Grants - Individual (RGPIN)
Guo-Xing Miao	CFREF (Canada First Research Excellence Fund) NSERC - Discovery Grants - Individual (RGPIN)
Jon Yard	NSERC - Discovery Grants - Individual (RGPIN) University of British Columbia
Jonathan Baugh	CFREF (Canada First Research Excellence Fund) Mitacs Inc Mitacs Partner Contribution NSERC - Discovery Grants - Individual (RGPIN)
Joseph Emerson	NSERC - Discovery Grants - Individual (RGPIN) University of Innsbruck
Kazi Rajibul Islam	Ministry of Colleges & Universities (MCU) (formerly MEDJCT) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN) UW - Contribution
Kevin Resch	CRC - NSERC NRC - Other NSERC - Discovery Grants - Individual (RGPIN)

Matteo Mariantoni	CFI - IOF (Infrastructure Operating Fund) CFREF (Canada First Research Excellence Fund) NSERC - Discovery Grants - Individual (RGPIN)
Michael Reimer	CFREF (Canada First Research Excellence Fund) DRDC (Defence Research and Development Canada) Mitacs Inc Mitacs Partner Contribution NSERC - Discovery Grants - Individual (RGPIN)
Michal Bajcsy	CFREF (Canada First Research Excellence Fund) NSERC - Discovery Grants - Individual (RGPIN) Sony
Michele Mosca	JPMorgan Chase and Co Massachusetts Institute of Technology Mitacs Inc Mitacs Partner Contribution NRC - Other NSERC - Alliance Grants NSERC - Discovery Grants - Individual (RGPIN) PWGSC - Other
Na Young Kim	CFREF (Canada First Research Excellence Fund) Ministry of Colleges & Universities (MCU) (formerly MEDJCT) - ORF-RE (Ontario Research Fund - Research Excellence) NSERC - Alliance Grants NSERC - CREATE (Collaborative Research and Training Experience Program) NSERC - Discovery Grants - Individual (RGPIN)
Norbert Lütkenhaus	DRDC (Defence Research and Development Canada) Honeywell International Inc NSERC - Alliance Grants NSERC - Discovery Grants - Individual (RGPIN)
Raffi Budakian	NSERC - Discovery Grants - Individual (RGPIN)
Raymond Laflamme	Keysight Technologies Inc NSERC - Alliance Grants Perimeter Institute for Theoretical Physics
Richard Cleve	NSERC - Discovery Grants - Individual (RGPIN)
Shalev Ben-David	NSERC - Discovery Grants - Individual (RGPIN)
Thomas Jennewein	Canadian Space Agency CFREF (Canada First Research Excellence Fund) DRDC (Defence Research and Development Canada) Honeywell International Inc INRS University NRC - Challenge Pgm - Internet of Things: Quantum Sensors

	NRC - Other
	NSERC - Alliance Grants
	NSERC - Discovery Grants - DND Supplement
	NSERC - Discovery Grants - Individual (RGPIN)
	NSERC - I2I (Idea to Innovation Program)
	NSERC - Research Tools and Instruments Grants (RTI) Category 1
	University of Western Ontario
William Slofstra	NSERC - Discovery Grants - Individual (RGPIN)

IQC is also home to the following Research Chairs:

- Raymond Laflamme, Mike and Ophelia Lazaridis Chair (2017-2027)
- Christine Muschik, University Research Chair (2022-2027)
- William Slofstra, University Research Chair (2022-2027)
- Crystal Senko, Canada Research Chair (2020-2025)
- David Cory, Canada Excellence Research Chair Laureate (2017)
- Raffi Budakian, University of Waterloo Endowed Chair in Nanotechnology (2014-ongoing)
- Kevin Resch, Canada Research Chair (2013-2023)

And the following past Research Chair holders:

- Debbie Leung, University Research Chair (2015-2022)
- Michele Mosca, University Research Chair (2012-2022)
- Raymond Laflamme, Canada Research Chair (2002-2022)

Infrastructure–Mike & Ophelia Lazaridis Quantum-Nano Centre (QNC)

As of March 2023, there are 16 operational research labs in QNC.

Selected labs are listed below:

- Quantum Photonics Laboratory
- Satellite Quantum Key Distribution Laboratory
- Quantum Verification Laboratory
- Laboratory for Digital Quantum Matter
- Nano-Photonics and Quantum Optics Lab
- Trapped Ion Quantum Control
- Engineered Quantum Systems Laboratory
- Integrated Nano Electronics
- Laboratory of Ultracold Quantum Matter and Light
- Quantum Optics and Quantum Information Group Laboratory
- Quantum Information with Trapped Ions

IQC continues to improve the quality of our existing infrastructure. For example, the Quantum Outreach and Education Lab has been upgraded with a virtual recording studio to engage students and audiences with live presentations, including visual demonstrations and a lightboard. To support the lab's development of resource kits for students and teachers, a dedicated 3D printer has also been installed. In 2022-2023, the Quantum Outreach and Education Lab developed affordable educational demonstration kits to teach quantum key distribution, which were sent to 80 high school teachers in Canada and the United States. The lab was also able to live-stream experiments aimed at engaging participants remotely, and collectively taught fundamental quantum concepts to over 400 people this year.

Infrastructure–Quantum-Nano Fabrication and Characterization Facility (QNFCF)

QNFCF is responsible for three labs in the Quantum-Nano Centre's Metrology area: TEM lab, FIB lab and Dry Sample Prep lab. Open to researchers in government, industry and academia, over the past year the QNFCF reported a total of 34,515 hours of independent lab equipment use logged by registered lab users. This is the highest usage rate the lab has reported to date. Academic and industrial demand for lab time continues to draw significant interest from groups across Ontario and Canada.

- The total number of users has increased to 232 (from 209 in 2021-2022), including 47 users from industry.
- There is a growing demand for advanced laboratory facilities in Canada, as 75 research groups used QNFCF facilities (57 academic, 18 industry).

- 22 total institutions (four academic and 18 industry) use the facilities at QNFCF. This includes users from the University of Toronto and the University of British Columbia.
- A total 2,863 hours of process development activities resulted in the creation and characterization of multiple new processes and new technical reports to the benefit all registered users.
- Examples of growing private companies that use the facilities at QNFCF include Photonic Inc. (founded out of UBC) and Anyon Systems Inc. (Montreal) which consumed a combined more than 2,300 hours of time at QNFCF.

The QNFCF continues to benefit from IQC led initiatives to add new capabilities and improve existing research infrastructure. During the fiscal year 2022/2023 IQC contributed significant funding towards the acquisition of a new S/TEM system to replace an aging unit that was no longer supported by the original equipment manufacturer. The new JEOL JEM-F200 S/TEM equipped with a GAT 1065 GIF Continuum ER System for EELS & EFTEM analysis was successfully installed in Q1 2023. This system represents a major addition in terms of advanced electron microscopy capabilities and will be of great benefit to existing and future lab members.

The QNFCF also benefitted from an IQC led initiative funding a SUSS SB6 wafer bonding system (installed Q4 2022) and a JEOL IT-510LV Scanning Electron Microscope system (installed Q3 2022). The former addition will enable our community to pursue new wafer-scale microelectronic packaging techniques while the latter will enable electron lithography and microscopy in a multi-glovebox inert environment.

The IQC and CFREF-TQT (Transformative Quantum Technologies) programs support the QNFCF operations and in 2022-2023 contributed over $1.270M to cover staff salaries, equipment acquisitions and equipment service contracts.

Infrastructure – Research Advancement Centres (RAC)

As of March 31, 2022, there are seven operational research labs in RAC, six of which are led by a principal investigator:

- Quantum Materials and Devices (QMAD) lab
- Quantum Photonic Devices Lab
- Quantum Innovation (QuIN) Lab
- Quantum Photonics Lab
- Coherent Spintronics Lab
- Nanoscale Magnetic Resonance Imaging Lab
- Quantum Exploration Space

While the Quantum Exploration Space does not have a principal investigator, this is an impressive lab space that supports students enrolled in the IQC's MSc Physics

(Quantum Technology) program, offered at Waterloo in partnership with IQC and TQT. Two of the three lab-based courses required to complete the Quantum Technology degree are held in this lab and all three lab requirements are hosted there. Additionally, this lab is used to give students and IQC visitors access to real, research-grade quantum systems for laboratory experiments and knowledge building, such as during industry-IQC workshops that explore ways these companies can use quantum in their ventures. High school and undergraduate students in outreach programs such as Quantum School for Young Students (QSYS) and Undergraduate School on Experimental Quantum Information Processing (USEQIP) also benefit from detailed, hands-on experience with the real systems in the Quantum Exploration Space. In the future, this lab will allow IQC to showcase quantum devices in action to large numbers of industry experts and visitors. to witness quantum devices in action.

The RAC buildings also host numerous shared support labs, machine shops and wet chemistry labs that are required to support the research groups and QNFCF users as well.

Collaborations & Seeking New Partnerships

The IQC research community values opportunities for collaboration, both with other research groups and universities as well as with government, non-profits and private organizations. In 2022-2023, IQC faculty members collectively reported 197 active collaborations with at least 150 unique organizations that span the globe. The following list of organizations are an example, including universities, research institutes, private corporations, and government. A full list of collaborations can be found in Appendix D on page 80.

- Qubic
- Google
- National Research Council of Canada
- IBM
- Crypto4A Technologies
- National Institute of Optics, Canada
- Harvard University
- CERN
- SERENE-RISC
- University of British Columbia
- Georgetown University
- Simon Fraser University
- University of Western Ontario
- ETH Zurich
- University of Maryland
- NRC Canada
- Yale University
- Jet Propulsion Laboratory
- University College London
- Institute for Quantum Optics and Quantum Information (IQOQI)
- Quantum Algorithm Institute (BC)
- Institut Quantique
- Centre for Quantum Technologies
- National University of Singapore
- University of Texas at Austin
- Centre for Eye and Vision Research, Hong Kong

In addition to maintaining and growing established relationships, IQC's researchers and stakeholder groups continuously seek new partnerships to further strategic research objectives. This year, IQC engaged in relationship and partnership discussions with the following groups:

- Government of Canada: The leadership team at IQC meets regularly with representatives of the Government of Canada. As the leading quantum information institute in Canada, IQC is funded by the government and works collaboratively to advise the government on both progress and implications of quantum information science and technology research. Representatives from the Department of National Defence, National Research Council Canada, Canadian Security Intelligence Service, the Canadian Space Agency and Public Safety Canada all visited IQC in Fiscal 2022-2023. These interactions with various ministries ensure that the Canadian public can benefit from the investment the Government has made in quantum information science and technology.

- Foreign International Government – Interested Parties: Canada is among the world leaders in quantum information science and technology. Many of Canada's allies of Canada are working to build or contribute to ongoing quantum projects either by direct funding or promoting international collaborations. In 2022-2023 the Japanese Consul General, the Korea Foundation, the head of Science for the British Consulate General, the Trade Commission to the Netherlands, the

Ambassador of Italy in Canada and delegates from the French embassy all visited IQC. IQC is a plank in the bridge between Canada and these partner nations; all of which have direct ties to the work going on at IQC via trade, academic collaboration or scientific outreach.

- Large Multi-national Companies: While IQC is a draw for startups and QNFCF pulls in growing commercial partners from across the country, IQC is also a magnet for the largest and most quantum-focused companies in the world. In 2022-2023, IQC hosted visitors from IBM, Apple, Amazon, Microsoft, and Mitsubishi. These relationships result in the flow of information, and sometimes personnel, between these companies and IQC. These companies can supplement the funding of the Canadian Government, and in some cases, they may provide valuable resources, such as access to working quantum computers, which benefits our researchers enormously.
- Quantum Focused Emerging Companies: In addition to the largest companies in the world, IQC also advises and engages in projects funded by emerging companies from across the world. Examples of companies in this size range include Canadian companies such as Xanadu Computing Technologies, 1QBit, Anyon Systems Inc., Photonic Inc. and Crypto4A, and emerging international companies like Zapata Computing and KETS Quantum Security Ltd. Many of these companies and their founders have strong ties with IQC, having previously worked or studied in Waterloo. In addition, IQC sometimes acts as a matchmaker with these companies, developing Memoranda of Understanding (MOU) that utilize private sector equipment partners to further academic projects.
- Startups: IQC startups and the environment that enables their creation and success will be discussed later in this report.
- Venture Capitalists: Most IQC visits with venture capital groups this year focused on the Series A funding for evolutionQ in early to mid-2022. The Group Ventures and Quantonation engaged in several discussions with IQC leadership through the year, which exposes the entire Waterloo Quantum Ecosystem to new opportunities for funding to drive the development of quantum technologies. The cost to control quantum properties will generate an entirely new economy but the cost to do so will be significant; private capital needs to be involved in the early development stage of new technologies as well as in the final stage of developing quantum applications.
- Canadian Academic Groups: As the oldest and most prestigious quantum information institute in Canada, IQC is visited by representatives of other Canadian institutes with some regularity. Visitors in 2022-2023 include leadership teams from the Quantum Matter Institute at UBC, and members from PINQ2, which oversees access to IBM's quantum computer being constructed in Bromont, QC. IQC is in discussion with other Canadian quantum centres (e.g., Sherbrooke and Calgary) to look at developing a cross-Canada research network that will highlight and strengthen each centre's unique specializations while

ensuring that Canada as a nation has a clear and focused international narrative about our nation's quantum excellence to the rest of the world.

- International Academic Groups: The Korea Institute for Advanced Study and members from the Centre National de la Recherche Scientifique in France also had leadership level discussions with IQC in 2022-2023. These international conversations highlight the high level of research excellence at IQC and indicates our researcher's reputations as leavers in the global quantum community.

These examples of collaborations taking place at IQC reflect only visitors that represent opportunities for strategic growth, resource sharing and pooling of academic and technical expertise; later in this report, examples of visitors from the Canadian public and future quantum scientists will demonstrate the full scope of the action taking place at IQC.

Objective B

Provide opportunities for students to learn and apply new knowledge.

Expected Results: Support and create opportunities for students to learn and apply knowledge.

Planned Activities:

- Continuing to grow and attract the best talent to IQC's graduate program.
- Fielding at least 400 applications to the University of Waterloo/IQC graduate studies program.
- Expanding connections made with undergraduate programs at Ontario and Canadian universities.
- Continuing to host timely, focused conferences, workshops, seminars and courses as pandemic-related logistical restrictions are reduced.
- Hosting up to 100 workshops and seminars and colloquia.
- Jointly sponsor or host up to 10 workshops and conferences with national and international partner organizations.

Attracting Talent – Postdoctoral Fellows

Postdoctoral fellowship positions provide early career researchers with invaluable opportunities for additional mentoring, publishing, researching and teaching. In 2022-23, IQC recruited 15 new postdoctoral fellows, five of whom recently completed their doctoral studies at IQC. This ability to recruit internally is due to the strength of the IQC graduate program that has allowed IQC to continue world-class research and provide our recent graduates with the opportunity to take the next step in their careers, even while faced with significant travel restrictions.

Over the last fiscal year, IQC employed a total of 55 unique postdoctoral fellows, at least 14 of whom were women (26%). As outlined in the table below, newly recruited fellows came from prominent institutions in Canada and around the world.

Canadian	International
Université de Montreal, CA	Oxford University, United Kingdom
University of Western Ontario, CA	Harvard, USA
University of Waterloo, CA	University of Houston, USA
Queen's University	University of Oklahoma, USA
NRC Canada	

A full list of current postdoctoral fellows can be found in Appendix E on page 86.

Since 2021, 16 IQC PhD alumni have been awarded postdoctoral fellowships. These alumni represent a group of early researchers dedicated to advancing their work in quantum information at IQC. In addition to attracting highly qualified young researchers, IQC postdoctoral fellowships are a proven method to seed further quantum research across Canada with former IQC postdocs holding faculty positions at Mount Allison University, Université de Sherbrooke, McGill University, University of Ottawa, Carleton University, Toronto Metropolitan University and University of Waterloo, to name a few examples.

Attracting Talent – Graduate Students

IQC welcomed 52 new graduate students this past year from 558 applications, bringing the total current number of master's and PhD students to 207 (88 and 119, respectively). IQC accepts applications from some of the most prestigious schools across Canada and around the world. The table below illustrates the range of institutions our applicants come from, including applicants from eight of the 10 Canadian provinces (Prince Edward Island and Newfoundland and Labrador are not represented among our applicants).

Canada	International	United States
Universite de Montreal	Delft University of Technology	Columbia University
University of Calgary	ETH Zurich	Stanford University
University of Ottawa	Indian Institute of Technology Bombay	Massachusetts Institute of Technology
McGill University	University of Cambridge	California Institute of Technology
University of British Columbia	Federal University of Sao Carlos	Yale University

A full list of current graduate students currently studying at IQC can be found in Appendix F on page 86.

Attracting Talent – Undergraduate Students

IQC offers many opportunities to expose undergraduate students to research.

USEQIP

Students can apply in tandem with applications to the annual Undergraduate School on Experimental Quantum Information Processing (USEQIP) with the opportunity to stay for a research term following the program, or they can apply for a research associate position outright. With both opportunities, undergraduate students are provided an in-depth introduction to the knowledge skills necessary to succeed in a quantum information science graduate level program.

CO-OPERATIVE EDUCATION

While USEQIP is an excellent opportunity to attract talent from across the globe it is worth noting that IQC also takes advantage of the largest co-operative education system in Canada here at the University of Waterloo. Many of the labs at IQC expose various undergraduate students to the day-to-day operations of advanced labs. For example, Dr. K. Rajibul Islam's Quantum Information with Trapped Ions lab hired three co-op students per term (9 total) in 2022-2023 and engaged several undergraduate researchers as well. These students are exposed to advanced lab procedures and are occasionally named in publications with their principal investigators. Similarly, Dr. John Donohue, Senior Manager Scientific Outreach, employed three students over that time as well.

UNDERGRADUATE RESEARCH ASSISTANTS

Many of the participants in USEQIP follow the course with an opportunity to work in a lab for the remainder of the spring term (in spring 2022, 20 out of 24 USEQIP participants stayed in Waterloo and worked with IQC faculty members for the remainder of the term). However, undergraduate students do not need to attend USEQIP to become a URA. Many apply directly to the labs; Dr. Christine Muschik currently has two USEQIP URA's and one independent URA, for example.

For 2022-2023 IQC employed 87 URA's and co-op students in various roles in our labs.

Graduate Student Awards

The best and brightest minds are studying and researching at IQC, earning awards and scholarships in recognition of their work. These awards provide students with the funding needed to devote themselves to their studies and also demonstrate their research excellence. In the last year, 178 IQC students were collectively granted 660 separate awards/fellowships/scholarships.

Of the 178 IQC students that earned awards and scholarships, 35 were female (20%) and 7 additional awarded students did not report gender (4%). Overall, 89% of all IQC graduate students received awards including 71% of female students and 78% of non-reporting students, demonstrating the excellence of IQC students.

Additionally, when considering all graduates students, IQC continues to strive for gender equity with 59 women or gender non-reporting students in 2021-2022 and 56 in 2022-2023. The list below highlights some of these top awards, scholarships and fellowships our master's and PhD students received:

- Six Mike & Ophelia Lazaridis Fellowships
- One IQC Achievement Award
- 50 International Doctoral Student Awards

- Seven International Master’s Awards of Excellence
- 83 Marie Curie Graduate Student Awards
- One NSERC Alexander Graham Bell Canada Graduate Scholarships - Doctoral
- Three NSERC Alexander Graham Bell Canada Graduate Scholarships - Master's
- Six NSERC Postgraduate Scholarships - Doctoral
- Three NSERC Vanier Canada Graduate Scholarships
- 21 President's Graduate Scholarships
- One Raymond Laflamme and Janice Gregson Graduate Scholarship for Women in Quantum Information Science
- Four Ontario Graduate Scholarships
- One William Tutte Postgraduate Scholarship
- One Women in Mathematics Directed Reading Program Mentorship Award

Career Building

IQC has an enviable academic reputation. It also has an excellent reputation as an institution that fosters the development of its students and postdoctoral fellows. In 2022-2023 doctoral candidates and postdoctoral fellows published at least 22 peer-reviewed articles with no faculty member as co-author (13.5% of all publications), in some cases these students and fellows worked together and in some cases PhD students are the sole authors. For example, Erickson Tjoa, together with another Waterloo PhD candidate in physics published an article in Physical Review D in April 2022 which currently has 8 citations. Tjoa also has a number of papers where he is the sole author and H-index of 8 (before being granted his PhD). Similarly, Priyanka Mukhopdhyay published in the Journal of Computer and System Sciences (2 citations) in Februrary 2022 as a sole author and is currently named in 11 publications. Note that the theme of assisted career development and opportunities to build professional networks appears in many of the profiles that follow. Additionally, IQC students and postdoctoral fellows (8 at this time, split among 11 of the startups linked to IQC) are involved with commercialization of their research, either in partnership with faculty members or alone.

IQC leverages its academic reputation to draw in excellent students and postdoctoral fellows and provides those community members with opportunities to excel in their chosen careers, either in academia or in industry.

IQC Alumni: Building the Quantum Workforce

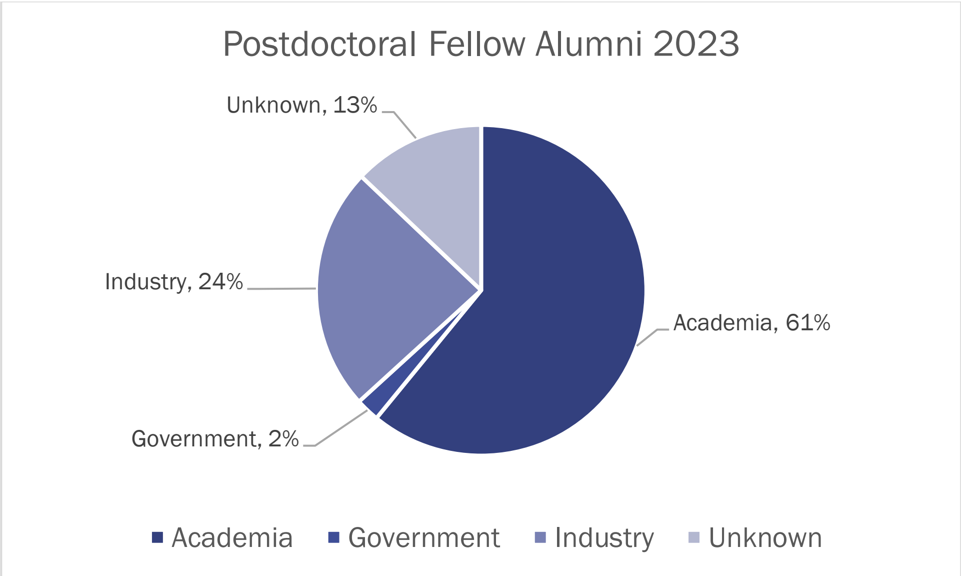
IQC students and postdoctoral alumni leave to become global citizens who have a profound impact on academic, industry and government sectors. They help shape quantum advancements across industrial sectors including banking, communications, and technology and inspire future generations of innovators with their passion, purpose and ingenuity.

Selected alum careers:

- Associate Professor
- Research Engineer
- Vice-president, quantum computing
- Senior scientist
- Director of Quantum Computing

Postdoctoral Fellows Alumni Overview

After leaving academia, postdoctoral fellow alumni are regarded as role models, visionaries and leaders of the quantum industry by their peers. Our alumni leave campus and become global citizens who impact academic, industry and government sectors. Below is a representation of where IQC postdoctoral fellows have gone as of March 31, 2023:



Postdoctoral Fellow Alumni Profiles

Simone Severini – Postdoctoral Fellow 2007-2009

Dr. Simone Severini learned about the field of quantum computing in 1997 and became hooked. A year later, he visited the UK to talk with people working in quantum information, including then PhD student Michele Mosca, who soon became one of the founding members of Waterloo's Institute for Quantum Computing. A decade later, Severini also joined IQC, as a postdoctoral fellow with Dr. Mosca, where he worked at the interplay of combinatorics and quantum physics.

Following his postdoctoral research at IQC, Severini held several academic positions before becoming a manager at Amazon Web Services (AWS). In his current position, Severini's goal is to accelerate innovation in quantum technologies. He describes his role as one where he can hope to contribute positively to science with a deep impact, "without writing scientific papers."

At AWS, Severini has worked to design and develop their quantum strategy. He contributed to the launch of Amazon Braket, a managed quantum computing service that gives researchers and developers access to different types of quantum hardware, as well as helped structure the Amazon Quantum Solutions Lab that works with customers to research and identify the most promising future applications of quantum computing for them. Severini also co-founded both the AWS Center for Quantum Computing and the AWS Center for Quantum Networking, both of which work with academia to address different challenges for the future of quantum computing.

"IQC helped me to appreciate the importance of collaboration and teamwork for the first time in life," said Severini. "When you are in a building and you can talk to computer scientists, quantum physicists, mathematicians, and many people with different backgrounds, something is ought to happen. You find common interests or complementary skills."

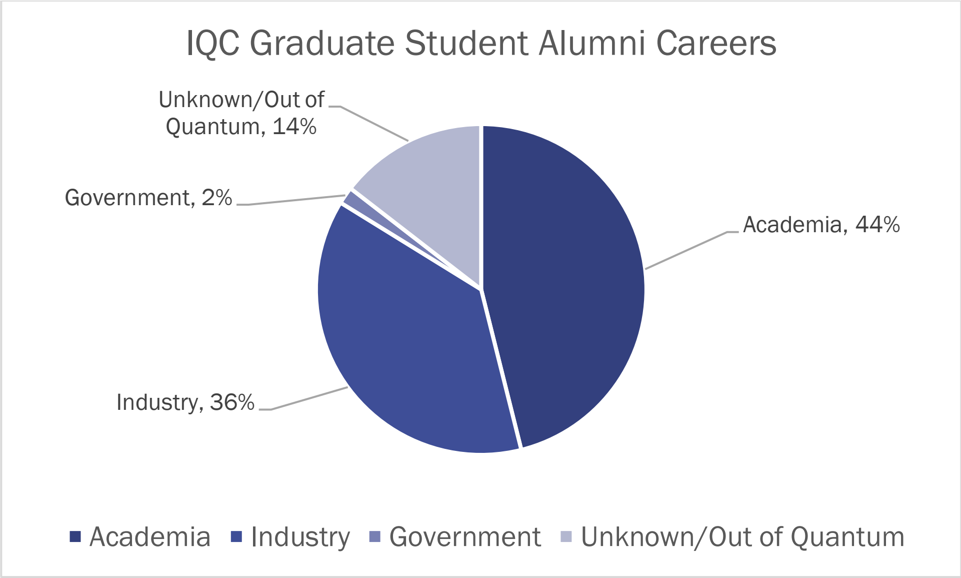
Sarah Sheldon – Postdoctoral Fellow 2013

During her most recent return to IQC, former postdoctoral fellow Sarah Sheldon instructed a session on IBM's Quantum Experience, a cloud-enabled quantum processor, with a room of Undergraduate School on Experimental Quantum Information Processing (USEQIP) participants. Sheldon is part of the experimental quantum computing team at IBM Research that is currently pursuing a quantum computing architecture based on superconducting qubits and error corrections through surface code. She is developing new calibration and characterization techniques to better understand the errors present in the quantum system.

"The research I did while at IQC was very relevant for my current position with IBM," said Sheldon. She earned her PhD at the Massachusetts Institute of Technology (MIT) in Nuclear Science and Engineering with advisor David Cory. Sheldon studied nuclear magnetic resonance (NMR) and electron spin resonance (ESR), focusing mostly on dynamic nuclear polarization (DNP) and quantum control. As a postdoctoral fellow at IQC, Sheldon was exposed to different approaches to quantum computing research that motivated her to select a research group that incorporated both theory and experiment, engineering as well as basic science. “Quantum computing is such an interdisciplinary field. I think it’s beneficial to be in a research community like IQC or IBM where there are many people with wide-ranging interests and backgrounds within the broader field.”

Graduate Students Alumni Overview

This year, IQC proudly forwarded 29 masters students and 7 PhD students, for advanced degrees bringing the total number of student alum to 415 cumulatively. These graduates are employed in a diverse range of positions, from academia to industry and government, both within Canada and around the world. As of March 31, 2022, 127 (30%) IQC graduates are working in the Quantum Information (QI) field in Canada, of which 27 are women. At least nine IQC graduates are employed as postdoctoral fellows at Canadian Universities. The chart below indicates the sectors where IQC graduate students have moved on to after leaving IQC, where known.



Student Alumni Profiles

Maris Ozols - (MMath Combinatorics & Optimization, PhD Combinatorics & Optimization)

Dr. Maris Ozols found himself as an IQC graduate student through what he describes as “a sequence of accidents.” After choosing computer science as an undergraduate because that’s what everyone else was studying and it aligned with his interests, he found a quantum computing professor who would take him on as a research intern. This professor also had connections with an IQC researcher, who took Ozols on as an intern the next summer. After coming to IQC during his undergrad, “the rest was history!”

Ozols is now a professor at the University of Amsterdam, where his research combines optimization and representation theory with applications in quantum information. In his research, his focus is building mathematical and computational tools to share with other people. His goal is to discover something beautiful with his research and help others go further, creating new techniques and models which can enable solving large classes of problems.

“My work at IQC laid the foundation for quantum algorithms and quantum information, both of which I am now working in,” said Ozols. “It was a great place to build an academic network and connections and fostered a sense of community within quantum. Once you live in Waterloo long enough, you meet enough people, and that gives you the feeling that you’re at home.”

Chris Erven – (Masters, PhD Physics-Quantum Information)

Dr. Chris Erven was inspired by IQC’s Dr. Michele Mosca during his undergraduate degree in engineering at Waterloo, seeing quantum information and cryptography as an opportunity to combine the intricacies of quantum physics with the hands-on practicality of engineering. Erven then earned both his masters and doctoral level degrees at IQC under Dr. Gregor Weihs and Dr. Raymond Laflamme. His work on quantum key distribution (QKD) systems included developing a working real-time system between rooftops on the UW campus (CEIT, BFG, RAC) and the Perimeter Institute, and from the RAC building to fields surrounding it. In one memorable investigation, Erven describes placing half of his experimental set up in Dr. Raymond Laflamme’s office, IQC’s Executive Director at the time — a testament to IQC’s collaborative and tight-knit culture.

After leaving IQC, Erven recognized a gap between academia and industry and co-founded the Quantum Technology Enterprise Centre (QTEC), a quantum startup incubator, at the University of Bristol while working their first as a Postdoc and then Lecturer. In parallel, he also founded KETS Quantum Security with 3 co-founders to commercialise their pioneering work in chip-based quantum cryptography. As CEO, he sets the strategic direction of KETS and spends his days talking with investors, customers, and managing the team. “I hope that my work has an impact on commercializing quantum-safe security,” says Erven. “In today’s world, we don’t go 30 seconds without touching digital technology of some kind, all of which is networked, none of which is quantum-safe. KETS aims to change that.”

Erven credits UWaterloo and IQC with his entrepreneurial inspiration, having “caught the bug for startups” during his coop terms as an undergraduate, and as a student in the early days of IQC. He saw IQC as an “academic version of a startup”, encouraging an open mindset to start new projects without being afraid to fail. Also, being so close to RIM and hearing multiple talks from its founder Mike Lazaridis, who also gave IQC its start, was a huge inspiration.

Major Conferences

Quantum Connections

IQC is pleased to be hosting in-person conferences in Waterloo post pandemic as demonstrated by the inaugural Quantum Connections conference presented in early May 2023. While this conference lies outside the reporting period under review, the work required to plan and execute this the conference took place in this reporting period. The conference was inspired by an event held at the NRC before the pandemic, where the Quantum community came together in person. People commented on how great it was for the Canadian community to be together and wondered why it didn't happen more often. IQC recognized a gap in the quantum conference community and aimed to fix it with Quantum Connections. This conference focused on providing attendees with many networking opportunities, with an aim to foster new collaborations and creating connections between the academic, industrial and government sectors. A mix of panel discussions and keynote presentations critically examined the challenges that Canada is facing as the global quantum ecosystem expands, and offered suggestions and proactive steps that quantum professionals can take to ensure that Canada continues to have an enduring continued momentum within the global quantum landscape. Quantum Connections was an incredible success, attracting over 150 quantum professionals to engage in the two-day conference, and the feedback from speakers, panelists, attendees and participants has been overwhelmingly positive. Plans are already in place to make this an annual spring conference moving forward.

In addition to the first Quantum Connections conference, several more academic-focused conferences are discussed later in this report.

Seminars & Colloquia

With frequent events, IQC's schedule of seminars and colloquia consistently keep the research community and their respective visitors engaged. This past year, IQC hosted 78 seminars, 32 of which were delivered by and for students, and 10 colloquia. The student seminar series introduced in FY 2019-2020 continues to serve to connect IQC members, allowing students to share results of their ongoing research, to be exposed to research outside of their core research area, and to serve as a platform to develop presentation skills. The total number of seminars increased as we emerged from workplace restrictions. It's worth noting that the pandemic era investments in various support equipment continued to be used as several of these seminars were recorded or broadcast live on YouTube.

On YouTube, seminars and colloquia significantly expand the viewership beyond the live attendees with a much more diverse engagement ('Quantum Steampunk' for example had questions from both online and in person attendees – 11 questions/comments from the online audience during the live broadcast). The demonstrated interest in these topics has inspired IQC to continue uploading these sessions in the future. The impact of social media as an outreach and recruiting tool is discussed later in this report (see page 58).

Sponsored Conferences & Workshops

IQC commits to supporting external conferences and workshops to encourage opportunity for collaboration among a domestic and global network of researchers. In 2022-2023 IQC sponsored the following external partner events and remains committed to supporting relevant events as opportunity increases:

Date	Conference	Location
May	JAM Hacks 6 (Waterloo)	Virtual
June	Canadian Association of Physicists (CAP) Congress	McMaster
July	Stinson66	Fields Institute, Toronto
July	Theory of Quantum Computing (TQC)	University of Illinois Urbana-Champaign
July	13th International Conference on Materials and Mechanisms of Superconductivity & High Temperature Superconductors (M2S)	Vancouver
September	3rd international Workshop on Programming Languages for Quantum Computing	Ljubljanan, Slovenia
October	Canadian Undergraduate Physics Conference (CUPC)	Guelph
January	Quantum Days	Virtual

Supporting these conferences builds the IQC brand for recruiting future students (JAM Hacks 6 is a high school conference, Canadian Undergraduate Physics Conference) and future postdoctoral fellows or faculty building their careers.

Promote collaborations through participation in national and international conferences

IQC is dedicated to finding opportunities to participate in national and international conferences. IQC faculty were collectively asked to speak at over 100 conferences with organizers from around the world. The below list highlights selected scientific conferences IQC members were invited to speak at and/or attended. A complete list of conference participation is listed in Appendix G on page 90.

- Single-photon source based on a quantum dot emitting at cesium wavelength, SPIE Photonics West
- Nanophotonic platforms for quantum optics with atomic ensembles, CAP Congress
- Angstrom-scale nuclear magnetic resonance diffraction: a route to atomic resolution magnetic resonance imaging, Nano MRI-7, Barcelona, Spain
- The Role of Randomized Compiling for Quantum Computing: from NISQ to QEC, SFB BeyondC, Vienna, Austria
- Classical algorithms for Forrelation, Los Alamos National Laboratory Summer School on Quantum Computing (online)
- Trapped Ion Quantum Information Processing Effort at University of Waterloo, Cornell University

- Precise and programmable individual optical addressing for Yb+ and Ba+ qubits, North American Conference on Trapped Ions (NACTI), Duke University
- Site-selective dissipation and measurement without decohering neighbours in a static ion chain, ETH Zurich
- Transitioning Quantum Technologies to a Business, 2022 CAP Conference
- The quantum internet and why satellites will be needed, QIT46 Symposium
- The platypus of the quantum channel zoo and their generic nonadditivity, CMS 2022 Winter Meeting
- Landau-Zener tunneling: from weak to strong environment coupling, APS March Meeting
- The demonstration of switchable coupling between a two-level system and a waveguide implemented using superconducting systems, 6th International Workshop on Quantum Coherence, Control, & Computing
- Next Challenges in Quantum Simulation, APS March Meeting
- Neutron Interferometry for Metrology, QSQS 2022
- Quantum nanophotonic devices for quantum computing, communication, and sensing, The Annual Conference of the IEEE Photonics Society
- MIP*=RE: what it is and further directions for operator algebraists, MFO, Oberwolfach workshop on C*-algebras
- 2D Heterostructures for Broadband Photodetection and Spectroscopy Beyond the Diffraction Limit, International Workshop on Quantum Circuits in 2D Materials, University of Ottawa
- Analog Quantum Simulation of Topological Models, Quantum Information Science for Nuclear Physics, Santa Fe, New Mexico
- Arithmetic of quantum circuits and SIC-POVMs, FoQaCiA kickoff meeting
- Quantum state control of ultracold chemistry, Cold Atom Molecule Interactions (CATMIN) Conference
- Quantum Simulations of Fundamental Interactions (QFun) engaging the community at the Perimeter Institute.

Organize conferences with multidisciplinary participants

IQC hosted many multidisciplinary meetings and conferences in 2022-2023.

Toronto Ultracold Atom Network (TUCAN) is a network of ultracold atomic researchers in Ontario. IQC's Ali Binai-Motlagh and Dr. Rajibul Islam hosted this group on Wednesday, May 18, 2022. In addition to being an academic conference on multiple topics (trapped ions, optical lattices, Bose-Einstein condensates) this meeting strengthened the ties between ultracold atom groups in Ontario.

Quantum Key Distribution (QKD) Summer School, which provides a solid foundation in relevant approaches and techniques to enable graduate students and young postdoctoral fellows to perform their own independent research, returned in 2022. In addition to a theoretical, week-long, academic foundations conference on theory, QKD also included a three-day workshop providing hands-on, project-based experience with open-source numerical QKD software tools. This conference was attended by 46 graduate students and young postdoctoral fellows from across Asia, Europe and North America.

Quantum Innovators (QI) is a three-day workshop that brings the most promising young postdoctoral fellows to Waterloo to present their network with peers and present their research to an audience of experts to refine their skills and presentation styles. In 2022, QI was offered in two streams, the first stream recruited fellows from science and engineering fields and was held on October 3-5, 2022. Twelve postdoctoral fellows from the world's most prestigious universities (Harvard, MIT, NRC Canada, ETC Zurich and Princeton, among others) came to Waterloo and discussed their work with IQC faculty and students. Later, from October 17-19, 16 postdoctoral fellows in computer science and mathematics arrived in Waterloo to discuss their research with the IQC community. Attendees arrived from Caltech, Centrum Wiskunde & Informatica, Technical University of Munich and Stanford (among others).

IQC has fully embraced the return of in-person, multidisciplinary conferences.

Objective C

Raise awareness and knowledge of quantum information science and technology in both the scientific community and amongst Canadians more generally.

Expected Results: Increase awareness and knowledge of quantum information science and technology and the Institute in both the scientific community and amongst Canadians more generally.

Planned Activities:

- Hosting USEQIP (undergraduate) and QSYS (high school) summer schools
- Hosting the annual high school teacher's workshop (Schrödinger's Class)
- Hosting outreach events including public lectures to increase the knowledge of event participants on quantum information and IQC
- Presenting dedicated STEM programming for women and girls
- Establishing relationships with key strategic partners to further share IQC's research discoveries
- Continuing to share IQC's research through publications, new stories/press releases, web and social media platforms
- Leveraging online resources and content to drive new visitors to IQC's website

Increase Awareness

The IQC outreach team, through virtual and in-person events, reached over 9500 people this year. More than 9000 of the people engaged with these talks were Canadian elementary or high school students or the general public, providing context and education for the broad enthusiasm surrounding the quest of a quantum computer in popular press and fiction.

In addition to the strategic development tours mentioned earlier, IQC also engages wider audiences with a guided tour through various labs located in the QNC building. Some tours in the past year include MITACS, EinsteinPlus (teachers' workshop), Girls in Quantum, the Governor General's Canada Leadership Conference, Collision Conference Waterloo Ecosystem tour and various members of the local community.

Faculty members at IQC are also actively engaged with non-academic outreach. Dr. Michele Mosca has been advocating for the use of quantum safe cryptography for a number of years, having realized some time ago that some data holds its value for decades. These efforts have resulted in Dr. Mosca's membership in the *World Economic Forum's Global Future Council on the Future of the Quantum Economy* and his participation of an in-person White House Roundtable dialogue in Washington D.C. on the topic of 'Pursuing Quantum Information Together: 2N vs 2N".

Another example is Dr. Alan Jamison's participation in a panel discussing the Future of Quantum Computing with respect to Intellectual Property (IP) Law in the U.S. hosted by Holland and Knight.

IQC members are involved in setting the rules that will govern the use of quantum technologies including examining the potential economic and legal impacts and these technologies become more accessible.

Faculty members are also engaged with the broader potential of quantum technologies. Dr. Michael Reimer participated in a National Institute of Health (NIH) workshop on the "Near-term Applications of Quantum Sensing Technologies in Biomedical Sciences."

Most IQC Faculty are involved in the Transformative Quantum Technology (TQT). TQT is a CFREF program led by IQC Faculty member Dr. David Cory. This includes the 'Quantum for Health Design Challenge' held in 2023, which resulted in the funding of two potential vision-care solutions based on quantum approaches.

IQC faculty members Dr. Matteo Mariantoni and Dr. Adrian Lupascu helped to organize a 'Build your own Superconducting Quantum Device' Workshop with CMC Microsystems, which was sponsored by Siemens. This workshop was targeted at Canadian graduate students and demonstrates the hands-on workshop style approach highlights how close to production quantum devices are for Canadians.

Dr. Adrian Lupascu began working with the Superconducting Quantum Materials and Systems Center (SQMS) at Fermi National Accelerator Laborartory (Fermilab) in January 2023. Fermilab houses the most powerful accelerator in North America (most powerful in the world until the LHC was opened). IQC is able to engage in partnerships with some of the most powerful labs in the world.

In addition to public outreach and engagement with the wider social implications of research into Quantum Information Science, IQC also has longstanding and successful programs to engage target audiences.

Quantum Information Science Engagement Programs

Undergraduate School on Experimental Quantum Information Processing (USEQIP)

The impact of programs like USEQIP has inspired past participants to further their academic studies at their home institution, and then return to IQC for graduate school. Since the program's inception in 2009, dozens of past USEQIP participants have returned to IQC to pursue graduate studies, proving it to be a useful recruitment tool for top talent. USEQIP participants note that advanced degrees seem more accessible after participation in the program and are attracted to IQC for continued study opportunities in particular:

> *"Thanks a lot to all of the people involved in the organization of the program, I enjoyed it a lot and it made me feel certain about my career path. Awesome job."*

“USEQIP taught me a lot about QIP and also revealed a lot about what academia is like – something which will be very useful for any potential career of mine!”

“Currently starting a research internship on laser cooling and ultracold atoms. Hopefully, I can participate in Dr. Jamison's group later in my studies.”

In 2022, IQC hosted its annual USEQIP program from May 30 to June 10. USEQIP returned to being an in-person experience in 2022. Talented students from across North America, Europe and Asia with representation from the Technical University of Munich, IIT Bombay, Bryn Mawr and Amherst College attended in 2022. Many Canadians also attended from McGill University, University of Ottawa, the University of British Columbia, Dalhousie University, and the University of Waterloo. From 266 applicants, 24 students were selected to come to Waterloo for the intense program. Of those students, 21 stayed for the term working as a URA with various faculty members and gained invaluable experience working with leading researchers. USEQIP also reached gender parity this year with 12 men and 12 women participating in the program.

Quantum School for Young Students (QSYS)

IQC hosted its annual QSYS summer school in two streams in July 2022; July 11 to July 15 was a virtual school and July 25 to July 29 was in-person.

By hosting QSYS as a dual-stream event IQC was again able to surpass its annual high-water mark for student attendance with 152 students attending. In August 2021, the enrolment was 136 students for the second virtual delivery of the program. QSYS’s jump in enrolment indicates an extraordinary appetite in quantum topics for high school-aged students, and it also highlights IQC’s reputation as a world-class institute for quantum information science research. In addition to an excellent curriculum QSYS in also an inclusive environment for young people reaching nearly gender parity this year with 47% participation by women and other equity deserving genders.

The virtual stream also allowed IQC to expand and showcase its work to younger audiences from Asia, Africa, North and South America and Europe.

In a follow-up survey to students once the summer school had concluded, 97% of respondents rated their overall experience at QCSYS as excellent (72%) or good (25%). 100% of respondents said that they would actively encourage people to apply (66.7%) or if asked, they would encourage people to apply (33.3%). 83.6% of respondents strongly agreed with the statement, “QSYS exposed me to ideas not available in my high school classes.”

“QSYS was a really amazing opportunity to learn more about an interesting and not really talked about subject. A great way to connect with the science community. And a great way to get a taste of my dream university, the University of Waterloo!”

“I wish QSYS can be longer, like around 3-4 weeks.”

Schrödinger's Class

IQC hosted its annual high school teacher workshop, Schrödinger's Class, from November 18– 20.

Schrödinger's Class also returned to in-person delivery for 2022. Schrödinger's Class reached near gender parity this year with 19 women among the 39 high school physics teachers at the conference.

In the post-workshop survey, 95% of respondents replied that they would "actively refer colleagues to the program" (90%) or "refer if asked about the program" (5%). When asked "How many teachers would you share Schrödinger's Class material with?" on average each participant answered that they would share this material with an additional 11 teachers.

> *"I loved everything. I know that is not very helpful but it's true. I would be nice if some of the equipment was made available for purchase at cost from the IQC. Lasers and polarizers can be expensive, especially for a small school like mine with minimal budget for science equipment. It would also be great if we could purchase some sets or individual components (especially the 3D printed parts) for those that do not have access to a 3D printer. Thank you so much to everyone who was involved in making this amazing experience happen. You all have my everlasting gratitude and appreciation."*

> *"Jonathan was absolutely amazing; he was very generous with his time, explanations, enthusiasm and energy. I really loved the first demonstration when he introduced the 45 degree polarizer between the horizontal one and the vertical one. Loved the photoelectric effect experiment, the super cooling magnetic levitation, the experiment with interferometers, the uncertainty experiment. I did not understand QKD very well but I guess I need to focus more to get it. Thanks also to Kim, and to the undergraduate student who accompanied Jonathan and who was extremely helpful. All in all, I felt the whole workshop was like a precious gift and I am so grateful. You guys are the best!"*

Public Lectures

IQC continued a series titled 'Quantum Today' that addressed the overall need for more scientific content designed to keep the scientific public aware of the current problems and potential solutions in quantum information science being developed and researched at IQC.

'Quantum Today' featured the work of five research groups at IQC and garnerd over 5000 virtual views combined and included:

- Michael Grabowecky giving a talk called 'Bounding the Deviations from Quantum Theory'
- Matthew Day discussing 'Noise Limits on Atomic Quantum Control'
- Melissa Henderson discussing 'Revealing Spin Structures with Neutron Beams'
- Michael Reimer and. Sasan V. Grayli discussing 'Metamaterials for Broadband Light Absorption'
- Annelise Bergeron, Francois Sfigakis, and Jonathan Baugh discussing 'New Platforms for Two-Dimensional Electron Gases'

In addition to talks focused on current research at IQC, an additional series titled 'IQC Alum Lectures' was also started to highlight both the current research of IQC alum, as well as to discuss their career paths. Participants included:

- Ben Criger (currently postdoctoral researcher at QuTech and an online instructor for TUDelft Online)
- Urbasi Sinha (faculty member in the Light and Atomic Matter Physics group at the Raman Research Institute in Bangalore India)

IQC also hosted two book talks for new releases related to relevant topics over the course of the year:

- 'Quantum Steampunk: The Physics of Yesterday's Tomorrow,' by Nicole Yunger Halpern on May 17, 2022, at the Waterloo Public Library
- 'Quantum Bullsh*t' by IQC Alum Chris Ferrie on July 15, 2022, hosted at QNC

John Donohue, Senior Manager, Scientific Outreach also held an evening lecture aimed at general audiences, hosted by the Kitchener Public Library on September 22, 2022, in the Main Library. The talk was titled 'Quantum – Separating Science Fiction from Science Fact' and was designed to speak to how quantum science enters mainstream thought.

High School Visits

IQC has continued to offer virtual class visits to high school physics classrooms across Canada. In these visits, quantum experts join a class virtually and share a presentation about quantum science and quantum information, taking questions from students about the field and pathways into research careers. IQC also returned to in-person class visits this year, reaching 2400+ high school students in 84 classroom visits (69 virtual and 15 in-person). Even with the excitement around returning to in-class visits it is worth noting that educators as far away as Turkey requested virtual visits from IQC experts. Elementary schools also benefitted from classroom visits with more than 660 students in over 18 class visits (15 in person) getting a first-hand look at quantum information science. The return of in-person science fairs also presented IQC with an opportunity to engage kids in learning about Quantum Science. Three in-person science fairs (LUMEN, TriCon and THEMUSEUM Family Hack Jam), resulted in more than 2600 kids of various ages interacting with postdoctoral fellows, graduate students, undergraduate students and specialists with an interest in QIS.

Promoting Science for Women & Girls

In addition to the work with CAGIS mentioned above, IQC had several events that focused on promoting gender equity in STEM fields spanning various audiences. IQC had representation at PhysiX: Girls Matter – Making Quantum Waves workshop aimed at middle school-aged girls in person at the University of Waterloo, Women in STEM (WiSTEM) workshops supporting high school aged girls, a broader discussion of how to advance equity and diversity in Science for the IQC community and the general public called “Actions to Advance Equity, Diversity and Inclusion in Science” delivered by Dr. Rowan Thompson, Dean for Equity, Diversity and Inclusion at Carleton University and Candice Harris, a research assistant, also at Carleton. All these events underline IQC’s commitment to increasing gender equity at IQC and also to fostering a more inclusive environment where enthusiasm for ideas is spread widely and indiscriminately across Canada.

As part of IQC’s commitment to equity and diversity, we strive to open doors for girls and women before they can apply to graduate school so that STEM-related graduate school is a viable opportunity. To drive gender parity, QSYS (high school students) had 49% women or non-binary attendees, USEQIP had 50% women attendees while Schrödinger’s Class (high school teachers) had 49% women attendees. By helping girls and young women to see themselves in quantum information science and technology, IQC strives to create a much larger talent pipeline for IQC and STEM programs in the future.

Strategic Outreach Partnerships

IQC has partnered with organizations including the Kitchener Public Library and THEMUSEUM to bring quantum ideas and associations into public spaces. IQC also has existing relationships with the Canadian Association for Girls in Science (CAGIS) WiSTEM and PhysiX, and remains committed to engaging with corporate and non-profit partners to promote quantum science. We are focused on building new partnerships in FY 2023-2024 to expand our ability to lead the quantum future in a Canadian context.

Communications

IQC ensures that researchers and their work are recognized worldwide through news stories, media releases, print and online platforms. Communications are tailored to ensure that stories are accessible to a broad range of audiences, from the general public to international members of the quantum community.

News Stories and Earned Media

With IQC members reporting research results each year, IQC strives to promote its community's work to the mainstream media. Between April 1st, 2022, and March 31st, 2023, approximately 1,100 media mentions of IQC were recorded, translating to a potential reach of nearly 1.2 billion impressions –the number of times that a post has been viewed on a feed.

Media outlets include but are not limited to:

- Forbes
- Yahoo! Finance
- The Globe and Mail
- Associated Press
- MIT Technology Review
- Science Business
- CBC
- Popular Mechanics

These outlets and more mentioned or cited IQC or IQC researchers in the last year, demonstrating IQC's global presence as a trusted expert in the international quantum industry.

Social Media

IQC continued to post informative and engaging content on social media for its followers throughout April 1, 2022, to March 31, 2023. Nearly 900 pieces of content posted across Twitter, LinkedIn, Facebook and Instagram generated 1,053,889 impressions, 12,453 interactions, and 32,205 engagements.

During the same period, the IQC YouTube channel garnered nearly 205,000 views and 42,500 hours of watch time, almost double the watch time in FY 21/22.

Throughout last year, IQC enjoyed steady growth across all its social media platforms. Below are some highlights of social platform growth from April 1, 2022, to March 31, 2023.

	New Followers	Total Current Followers	Increase in Total Followers
YouTube	2,359	26,925	9.6%
Twitter	2,405	18,869	14.6%
LinkedIn	7,277	10,932	199.1%
Facebook	339	5,880	6.1%
Instagram	246	1,759	16.3%
TOTAL	**12,626**	**64,365**	

Consistent online growth is a positive sign that points toward IQC's established position of being an authoritative voice in its field.

IQC continues to plan and implement new strategies to generate high quality, quantum-related content that is valuable for IQC's social media audiences and experiment more with targeted campaigns and evergreen content. Starting in late 2022, IQC began implementing new tactics to improve social media performance and engage audiences with a focus on audience engagement, growth, and retention.

IQC continues to position itself as a quantum authority, Canada as a global quantum leader, and quantum information science and technology itself as an endeavour worth understanding, supporting and developing further.

Objective D

Position Canada to take advantage of economic and social benefits of research by seizing opportunities and commercializing breakthrough research;

Expected Results: Canada is positioned to take advantage of economic and social benefits of quantum information science through seizing opportunities to commercialize breakthrough research.

Planned Activities:

- Supporting the building of a new quantum industry
- Promoting opportunities for IQC researchers to connect with Waterloo's entrepreneurial ecosystem through networking opportunities and formal events in partnership with the broader startup networks in Waterloo Region

Supporting Quantum Industry and Ecosystem Connections

IQC is at the centre of the emerging quantum industry in Canada. Companies, like Photonic Inc., or Anyon, despite being based in other provinces make operational pilgrimages to Waterloo to make use of the facilities located in Waterloo Region which has resulted in fulltime employees being located in the region. The environment of entrepreneurship at IQC combined with specialized knowledge emerging from an intensive research centre has created the necessary conditions for aggressive commercialization of emerging technologies.

As of March 2023, IQC researchers collectively held over 40 active patents, 30 licenses and two provisional patents granted in 2022-2023. Currently, IQC faculty have over 45 active patent applications pending approval.

IQC's research and innovative new technologies are influencing the development of new companies and creating a significant marketplace impact. To date, the below 21 currently active startups have emerged from IQC research.

IQC quantum spin-off companies:

- EvolutionQ
- Neutron Optics
- QuantumLaf Inc.
- Universal Quantum Devices
- SoftwareQ Inc.
- SpinQ
- Aquabits
- Northern Quantum Lights
- Groundstate Technologies
- UpScale Quantum Solutions
- Qubo Consulting Corp.
- High Q Technologies LP
- BioGraph Sense Inc.
- Qubic Inc.
- Single Quantum Systems
- QEYnet
- Foqus
- Q-Block Computing Inc.
- Aegis Quantum
- Incoherent Vision
- Chiral Quantum Inc.

NB: In the past, researchers were not required to report on patents or commercialization activities. The actual number of patents and/or licenses is not known and may be higher.

While nearly 45% of IQC principal investigators have commercialized their expertise and research through spin-off companies and patents, startups are also emerging from the labs and minds of research associates, postdoctoral fellows and graduate students. Additionally, the active mentorship of IQC faculty members also takes the form of advising quantum companies (both quantum and non-quantum firms), coaching early alum focused on careers in industry and collaborating with accelerator and business development hubs in and beyond Waterloo's quantum ecosystem.

IQC is aware that quantum startups have unique challenges to move from idea to prototype to a viable business. To assist in boosting startup success, IQC has begun building partnerships with startup incubators with a proven track record including the University of Waterloo's Velocity program and Creative Destruction Lab. How these incubators and accelerators can help quantum startups is described later in this report.

Transforming quantum ideas into impactful technologies

At IQC, research excellence and innovation go together. Its rich entrepreneurial culture attracts and supports quantum experts that choose to go beyond aspiration to develop impactful technologies. The most striking successes that have emerged from IQC post-pandemic are as follows:

- Keysight Technologies keeping Quantum Benchmark in Waterloo Region after acquiring it in Y2022 so that the company continued to thrive from the unique environment Waterloo's Quantum Ecosystem offers. The valuable technology at Quantum Benchmark was commercial tools for characterizing and validating quantum processors which will be integral to a working quantum computer.
- Startup evolutionQ raised $7M in series A funding in FY 2022-2023 (May). evolutionQ attracted the attention of SandboxAQ (an Alphabet spinoff) as well the venture capital firms The Group Ventures and Quantonation. evolutionQ ensures safety using Quantum Key Distribution, which fulfills the promise of privacy emerging from fundamental physical processes.

This unique environment has led to a growing startup community. This year's highlights include:

- Integrating quantum technologies into vision science applications with the first target being a structured light device geared towards the early detection of Age-related macular degeneration (AMD). (Dmitry Pushin, Dusan Sarenac and Connor Kapahi, Incoherent Vision)
- Developing an integrated photonic platform in an ultra-wide bandgap material for customisable and agile photonic devices at visible wavelengths. These devices will enable the commercialisation of atomic quantum technologies in portable form factors as well as find important uses in other applications such as coherent LIDAR. (Matt Day, GroundState Technologies)
- Developing quantum materials with exotic properties that will support next-generation information processing devices beyond semiconductor electronics, solving critical energy dissipation problems and enabling new functions and applications. (Alexandre Cooper-Roy, UpScale Quantum Solutions)

Promoting Entrepreneurial Ecosystems Opportunities

To ensure IQC's researchers have the direction and support they need to learn how to commercialize their research, IQC has partnered with different ecosystem stakeholders in the Waterloo Quantum Ecosystem and in the Waterloo-Toronto tech corridor to establish relationships with different stakeholders.

- Foqus, a startup we reported in 2021-2022 is taking full advantage of the entrepreneurial support that is available to founders, both in Waterloo and in Toronto. Foqus graduated from the Quantum Stream of the Creative Destruction Lab (CDL) program in 2021. Foqus has parlayed that accelerator experience into a membership in MaRS IAF (seed fund managers), IRaP Canada (Industrial Research Assistance Program), Communitech and Velocity.

- Incoherent Vision is also leveraging the ecosystem in Waterloo for commercial success. In addition to working on diagnosing human vision, IQC has its first member from the School of Optometry here in Waterloo, adding a new aspect to multidisciplinary studies. Incoherent Vision is working its way through the founder program and a similar program in Hong Kong (through their partnership with the Center for Eye and Vision Research in Hong Kong).

In September of 2022, IQC hosted Janice Vogtle, Trade Commissioner and Head of Office at Global Affairs Canada.

In November of 2022, IQC hosted Fanny Bousquet, First Secretary, Trade Commission to the Netherlands and the next day provided a tour for Tom Jenkins (Commissioner of the Tri-Lateral Commission along with Linda Hasenfratz, CEO of Linamar Corp among other North American leaders in business, government and academia).

In December, IQC leadership participated in an event to connect Canadian Quantum technology companies and organizations with leading U.S. companies, including Amazon/AWS and SandboxAQ.

By engaging in these meetings IQC leadership is actively working to create an environment that promotes a startup culture among IQC members. The result is that McKinsey and Company ranked Canada second in the world for Quantum startups in 2022 (Quantum Technology Monitor) with significant contributions from IQC in that ranking.

The potential for quantum technology is not a secret and the environment at IQC invites national and international interest and the interest of the private sector. The success of Canadian quantum projects is inextricably linked to the success of IQC, both commercially and academically.

IQC Canada Inc. – a new not-for-profit to expand quantum research

In 2022, IQC launched IQC Canada Inc., a not-for-profit arm of IQC with the goal of providing strategic commercial and market support to push quantum research beyond the boundaries of academic institutions. IQC and IQC Canada Inc. will embrace this new model and mobilize its expertise and resources to strengthen Canada's science, technology and innovation (STI) excellence and global leadership.

This NFP enables the Government of Canada to continue to be a strong partner in IQC in support of quantum research beyond the boundaries of academic research. IQC Canada Inc. is governed by a Board of Directors with the principal aim to support the development and advancement of quantum information science and technology at the highest international level and drive forward the implementation of IQC’s core activities in order to achieve the proposed outcomes and global leadership.

Ecosystem Collaborations to boost ecosystem success

IQC and IQC Canada Inc. are working with different quantum and quantum-enabled partners to assist in boosting the development and training of the Canadian quantum industry.

IQC has offered its support to CMC Microsystems' application to Critical Technologies Initiatives and collaborate to enable superconducting hardware fabrication and a testbed in Ontario. CMC Microsystems also draws on the expertise of the faculty members that serve on its Scientific Advisory board.

CMC has been providing quantum computing and hardware fabrication services to Canadian researchers and companies since 2022. Their experience in superconducting fabrication, global supply chain, network of researchers, and design software access services makes them an ideal candidate to help SMEs adopt our technologies in Ontario.

IQC is internationally established in experimental infrastructure for device fabrication and characterization and would like to work with CMC to make such services broadly available to CMC's users. This will be a mutually satisfying collaboration as it will IQC to employ CMC resources and services relevant for the development of our infrastructure and the fundamental research in the field of superconducting devices.

IQC is collaborating with Quantum Valley Ideas Lab (QVIL) on creating a bridge of talent to offer specialized internship and co-op placements with more undergraduate and graduate students in hands on quantum industry-specific projects. This will enable a strong ecosystem of developed talent and support a pipeline of ready-made jobs for graduates.

The IQC internship experience is a professionally-oriented program that connects students to the real world. By merging quantum skills with real-world business practice, graduates will be prepared to identify challenges – through their experience and will have the proven ability to propose, develop and implement timely, innovative solutions that enable quantum businesses to grow and prosper.

The four-month internship will facilitate a talent stream that expands the Canadian quantum talent stream and strengthens the Canadian ecosystem by ensuring graduates will have the opportunity to build and develop ready-made good paying jobs in Canada at graduation. As companies develop out of QVIL, the IQC internship program will be instrumental in growing the talent field and increasing needed highly valued workers.

The University of Waterloo has a world-renowned co-op placement program giving students two years of meaningful and relevant work experience, applying skills to real-life problems and a strong industry network by graduation. Based on market demand, IQC is partnering with three faculties, Engineering, Science and Math (which includes

Computer Science), at Waterloo to launch an undergraduate specialization in quantum information.

IQC's faculty already teach undergraduate courses and is therefore well situated to develop a talent stream of qualified and interested students to support the QVIL ecosystem. Having specialized co-op roles available through QVIL will ensure that the stream is supported as the quantum information undergraduate specialization grows and develops, which will assist in strengthening a strong ecosystem of trained talent for the Canadian quantum economy.

Objective E

Brand Canada as a place to conduct research in quantum information science and technologies

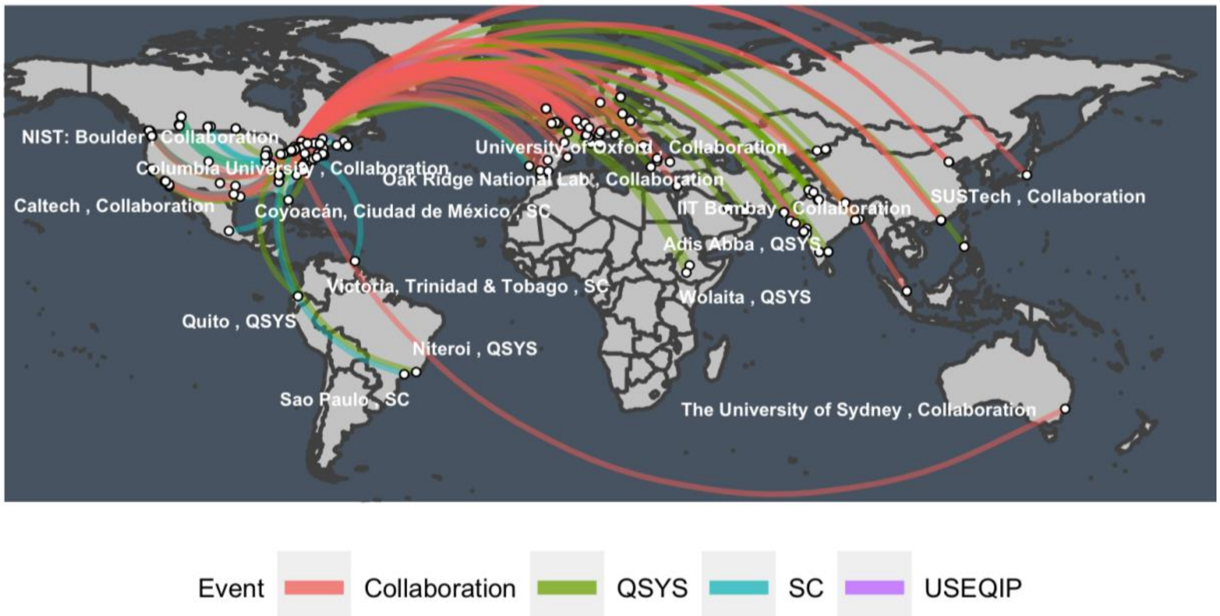
Expected Results: Brand Canada as a place to conduct research in quantum information technologies.

Planned Activities:

- Promoting Canada internationally as a place to conduct research in quantum technologies by participating in global quantum initiatives (including conferences, talks, seminars and other events)
- Being a catalyst for collaborations of quantum information scientists across Canada and around the world
- Promoting collaborations through participation in national and international conferences
- Producing internationally recognized, high-calibre publications co-authored by IQC researchers
- Organizing three conferences that involve multidisciplinary participants
- Continuing to host visits to IQC by international scientists and academics

Promote Canada as international place for quantum technology research through participation in global quantum initiatives

IQC Outreach and Collaborations - 2022



Quantum information research and technology remain a cutting-edge science. As one of the most comprehensive quantum research institutes in the world, IQC was responsible for developing its own talent pipeline. In 2022, the extent of IQC outreach is global. The map above illustrates only recruits to our pedagogical outreach programs, only for the year 2022. IQC takes quantum to the world and brings the world back to Waterloo.

Quantum leaders at the most prestigious universities worldwide came through IQC's training programs. Many of those alumni recommend recent or current members to IQC for further training. Rahul Jain (National University of Singapore, Centre for Quantum Technologies, Principal Investigator) was a postdoctoral fellow at IQC for 2 years (2006-2008). At least three of the graduate students he supervised served postdoctoral fellowships at IQC—Srijita Kundu (2017-2021), Anurag Anshu (2018-2020), and Priyanka Mukhopadhyay (2018-present). IQC has established a reputation of academic excellence and our faculty are training the next generation of scientists, promoting Canada as a world leader in quantum research and technology.

Be a catalyst for collaborations of quantum information scientists

In January 2023, Dr. Raymond Laflamme was named co-chair of the National Quantum Strategy's Advisory Council. The three key missions of the National Quantum Strategy are:

- Make Canada a world leader in the continued development, deployment and use of quantum computing hardware and software—to the benefit of Canadian industry, governments and citizens.
- Ensure the privacy and cyber-security of Canadians in a quantum-enabled world through a national secure quantum communications network and a post-quantum cryptography initiative.
- Enable the Government of Canada and key industries to be developers and early adopters of new quantum sensing technologies.

If those mission statements seem familiar review the IQC Statement of Objectives on page 5. Having spent more than 15 years successfully guiding IQC to the same missions it seems appropriate that Ray is now engaged with exporting IQC's methods to the entire Canadian quantum landscape. As he has said: "*I have seen first-hand the benefit of cultivating a dynamic quantum ecosystem here in Waterloo Region and look forward to being part of the working group's national approach to fostering a similar sense of community amongst quantum researchers and industries in all corners of our country.*"

Long-term Academic & Scientific Visitors

IQC hosts leading academic visitors from organizations around the world. These colleagues and collaborators come for several reasons and stay for varied amounts of time to conduct research, collaborate, share knowledge and present talks. Having fully recovered from the pandemic, IQC hosted 95 visitors from major research centres around the globe, leading quantum corporations, government advisors and startups interested in collaborating with like-minded experts:

Global Research centres	Major Corporations	Startups and Government
Max Planck Institute of Quantum Optics, Germany	Google	Craft Prospect Ltd
University of Toronto	Cambridge Quantum Computing	National Research Council Canada
Cornell University	Lockheed Martin	University of Texas at Austin
Korea Institute for Advanced Study (KIAS)	Microsoft Research	tO.technology
QuSoft, Research Centre for Quantum Software, The Netherlands	IBM Research	Bluefores Inc.

Global Research centres	Major Corporations	Startups and Government
Massachusetts Institute of Technology	NASA Jet Propulsion Laboratory	Xanadu Quantum Technologies

Over the last year, IQC has built new and strengthened existing relationships with other Canadian universities and organizations in quantum research and technology.

A strong indicator of Canada and IQC's leadership in quantum excellence around the world is the prestigious visitors who come and spend time at the Institute for research, collaboration and knowledge dissemination. IQC continually attracts top-ranking visitors from global research centres and corporations.

A full list of academic and scientific visitors can be found in in Appendix H on page 95.

Summary

This report has provided evidence that demonstrates IQC's track record of success in reaching its objectives. For the entirety of the funding relationship between ISED and IQC, IQC has set aggressive targets and met or exceeded those targets, resulting in its status as one of the leading quantum research institutes in the world. IQC has leveraged government funding into world-leading core faculty, highly cited research, innovative programs to support industry and direct economic benefits in Canada.

IQC has had a productive year. The Institute continues to attract top talent, leads in quantum information science and technology research and continually advances the frontier of quantum startups and their capabilities. IQC is the anchor of the Waterloo Region Quantum Ecosystem and is a place for Canada to look to for leadership and guidance as we support a national quantum vision.

APPENDICES

A. Risk Assessment & Mitigation

		LIKELIHOOD		
		LOW	MED	HIGH
IMPACT	HIGH	6	8	9
	MED	3	5	7
	LOW	1	2	4

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
Decrease in faculty negatively affects research output and reputation	High	Medium	8	IQC has a significant research output which contributes to ongoing reputational excellence. Decreasing faculty may negatively affect research output and consequently reputational excellence. Additionally, fewer faculty will necessarily result in a lower capacity for HQP supervision.	Continue to identify and implement new approaches to virtual collaborations. More aggressive recruiting in the face of increasing national and international competition for high performance individuals.
Transformational Technologies may render current research less relevant	High	Low	6	If IQC research is rendered less relevant, highly qualified personnel (HQP) and investment will go elsewhere.	Continued focus on relevant sub-fields in quantum information science and engineering. Engage quantum authorities outside IQC through our Scientific Advisory Committee to provide objective commentary on IQC research focus/ progress. Ongoing collaboration with partners to ensure research aligns with societal priorities and economic drivers . .

Difficulty recruiting the best and brightest HQPs	High	Med	8	Based on increased competition from private sector and new institutes with deep pockets investigating QIS.	Diversify markets/ countries from which students are recruited. Promote IQC sufficiently. Ensure excellent research, a world-class research environment with offering HQP unique opportunities and an inclusive community for HQP to success.

B. Publications

April 1, 2022-March 31, 2023

1. Gheorghiu, V; Mosca, M; Mukhopadhyay, P. (2022) A (quasi-)polynomial time heuristic algorithm for synthesizing T-depth optimal circuits .NPJ QUANTUM INFORMATION
2. Kundu, S; Sikora, J; Tan, EYZ. (2022) A device-independent protocol for XOR oblivious transfer .QUANTUM
3. Ng, KK; Zhang, C; Louko, J; Mann, RB. (2022) A little excitement across the horizon .NEW JOURNAL OF PHYSICS
4. Soda, B; Sudhir, V; Kempf, A. (2022) Acceleration-Induced Effects in Stimulated Light-Matter Interactions .PHYSICAL REVIEW LETTERS
5. Tansuwannont, T; Leung, D. (2022) Achieving Fault Tolerance on Capped Color Codes with Few Ancillas .PRX QUANTUM
6. Laflamme, R; Lin, JN; Mor, T. (2022) Algorithmic cooling for resolving state preparation and measurement errors in quantum computing .PHYSICAL REVIEW A
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C. Faculty Members, Research Assistant Professors & Research Associates

Faculty Members
Michal Bajcsy
Jonathan Baugh
Raffi Budakian
Shalev Ben-David
Richard Cleve
David Cory
Joseph Emerson
David Gosset
Alan Jamison
Thomas Jennewein
Na Young Kim
Raymond Laflamme
Debbie Leung
Adrian Lupascu
Norbert Lütkenhaus
Matteo Mariantoni
Guo-Xing Miao
Michele Mosca
Christine Muschik
Ashwin Nayak
Dmitry Pushin

Research Assistant Professor
Pooya Ronagh
Francoise Sfigakis

Research Associates
Brendon Higgins
Dusan Sarenac
Kimia Mohammadi
Vinodh Raj Rajagopal Muthu
Alexandre Cooper- Roy
Nigar Sultana
Sadegh Raeisi
Goutam Tamvada
Vinodh Raj Rajagopal Muthu
Joanna Krynski
Goutam Tamvada
Geovandro Pereira
Behrooz Semnani
Armin Jamshidpey
Matthew Day
Kimia Mohammadi

K. Rajibul Islam
Michael Reimer
Graeme Smith
Kevin Resch
Crystal Senko
William Slofstra
Adam Wei Tsen
Christopher Wilson
Jon Yard

Joanna Krynski
Dmitry Akhmetzyanov
Brian Neill
Yasar Atas
George Nichols

D. Collaborations – April 1, 2022 – March 31, 2023

Faculty Member	Company/Institution
Michal Bajcsy	Martin Houde from Western University, Canada
	Dr. E. Diamantis & Dr. I. Prassas , Mount Sinai Hospital, Canada
	Dr. P. Poole & Dr. D. Dalacu, National Research Council of Canada, Canada
	Fetah Benabid from xLim Research Institute in Limoges, France
	Philippe Tassin at Chalmers University, Sweden
	Prof. Konstantinos Lagoudakis, Strathclyde University, UK
	Prof. Arka Majumdar, U. of Washington, USA
	Retego Labs, USA
Jon Baugh	National Research Council of Canada, Canada
	Kennedy Labs (company; production of 2D materials and related devices), Brian Kennedy, President (based in Guelph), Canada
	Prof. Bhaskaran Muralidharan (research collaboration), Electrical Engineering Department,Indian Institute of Technology Bombay, India
	Prof. Aharon Blank (Technion Joint Research Program funded by Gerald Schwartz and Heather Reisman Foundation), Technion (Israel Institute of Technology), Israel
	Prof. Andrew Briggs' group (Department of Materials), Oxford University, UK
	Prof. Chandni Usha, IISc Bangalore, Department of Instrumentation and Applied Physics, India
Raffi Budakian	Dan Dalacu, National Research Council, Canada
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	IBM Research, USA
	Army Research Office, USA
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	Crystal Senko, University of Waterloo, Canada
	Sougato Bose, University College London, UK
	Zhexuan Gong, Colorado School of Mines, USA
	James Freericks, Georgetown University, USA

	Arnab Das, Indian Association for the Cultivation of Science, Kolkata, India
	Asmi Haldar, Max Planck Institute, Germany
Alan Jamison	Univerity of Chicago (David DeMille), USA, REDRUM (Researching Electic Dipoles with Radioactive Ultracold Molecules)
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	TRIUMF, UBC, Canada (REDRUM)
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	University of Vienna, Austria
	DotFAST, Austria
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	NSERC, Canada
	National Research Council, Canada
	CFI, Canada
	ORF, Canada
	Qeynet Inc, Canada
	ISED-ON, Canada
	Honeywell, Canada
	University of Waterloo, Canada
	University of Calgary, Canada
	University of Toronto, Canada
	McGill University, Canada
	Excelitas (formerly Perkin Elmer), Canada
	Canadian Space Agency, Canada
	National Institute of Optics (INO), Canada
	Xiphos, Canada
	Neptec, Canada
	McMaster University, Canada
	Fraunhofer Institut, Germany
	Politecnico di Milano, Italy
	University of Padova, Italy
	National University of Singapore, Singapore
	University of Bristol, UK
	Craft Prospect Ltd., UK
	University of Illinois, USA
	Jet Propulsion Laboratory, USA
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	Bhashyam Balaji, Defense Research and Development Canada (DRDC)
	Anthony Damini, Defense Research and Development Canada (DRDC)
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	Perimeter Institute, Canada
	Canadian Institute for Advanced Research, Canada
	Keysight technologies, Canada
	Institut Quantique (Sherbrooke), Canada
	Quantum Algorithm Institute (BC), Canada
	University of Guelph, Canada
	The Hong Kong University of Science and Technology, China
	Dawei Lu, SUStech, China
	Technion, Israel
	University College London, UK
	Phasecraft, UK
	Imperial College, UK
	University of California at Berkeley, USA
	University of Tennesse, USA
	Dept of Homeland Security , USA
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	Centrum Wiskunde & Informatica, Netherlands
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	University of Maryland, USA
	IBM, USA
	University of Illinois Urbana-Champaign, USA
	University of Boulder Colorado, USA
	Duke University, USA
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	MITACS, Canada
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	Department of Energy, FermiLab, Jefferson Lab, USA
	Defense Advanced Research Projects Agency (DARPA), USA
	MIT, USA
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	Defense Research and Development Canada (DRDC)
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	Michele Mosca, University of Waterloo, Canada
	Xiongfeng Ma, Tsinghua University, China
	Christoph Marquardt, Max Planck institute for the Science of light, Germany
	Renato Renner, ETH Zurich, Switzerland
	Daniel Gauthier, Ohio, USA

	Michael Reimer, University of Waterloo (IQC)
	Daniel Oi, University of Strathclyde, UK
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Michele Mosca	SERENE-RISC, Canada
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	QEYnet, Canada
	Crypto4a, Canada
	Creative Destruction Lab, Canada
	Rhea Canada Inc, Canada
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	Transumtex, Switzerland
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	KETS Quantum Security, UK
	National Institute of Standards and Technology (NIST), USA
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	University of Innsbruck, Wolfgang Dür, Austria
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	York University, Randy Lewis, Canada
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	Universitat Autònoma de Barcelona, Alessio Celi, Spain
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	Google, USA
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	Dave Touchette, University of Sherbrooke, Canada
	IRIF, Universite Paris, France
	Frederic Magniez, CNRS and University of Paris, France
	Jędrzej Kaniewski, University of Warsaw, Poland
	Rahul Jain, CQT and National University of Singapore, Singapore
	Máté Farkas, ICFO -- The Institute of Photonic Sciences, Spain
	Henry Yuen, Columbia University, USA

Dmitry Pushin	PROSPECT (Yale), USA
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	National Research Council of Canada, Canada
	University of Waterloo, Canada
	Delft University of Technology, Netherlands
	Royal Institute of Technology (KTH), Sweden
	CMC Microsystems, Canada
Kevin Resch	National Research Council, Canada
	Perimeter Institute, Canada
	University of Toronto, Canada
	University of Guelph, Canada
William Slofsta	NSERC, Canada
	Alfred P. Sloan Foundation, USA
Adam Wei Tsen	McMaster University, Canada
	Renmin University of China, China
	Chinese Academy of Sciences, China
	University of Freiburg, Germany
	Goethe-Universität Frankfurt, Germany
	Weizmann Institute of Science, Israel
	Cornell University, USA
	University of Michigan, USA
	Texas Tech University, USA
	University of Texas at Austin, USA
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	U.S. Army Research Office, USA
Crystal Senko	Sandia National Labs, USA
	Quantum Systems for Fundamental Science, USA
	Kazi Rajibul Islam, University of Waterloo
	NSERC (CRC Trapped Ion Quantum Computing)
Shalev Ben-David	Abhishek Anand (Caltech), USA
	Robin Kothari, Google, USA
Chris Wilson	Professor Ivette Fuentes at University of Austria, Austria
	Qubic, Canada
	Professor Enrique Solano at the University of Basque Country, Spain
	Professor Ozgur Mustecaplioglu at Koc University in Istanbul, Turkey
	Dr. Jose Aumentado, NIST-Colorado, USA
Jon Yard	University of British Columbia, Canada
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	University of Ottawa, Canada
	Uniwersytet Gdanski, Poland
	Laboratorio Iberico Internacional de Nanotechnologia , Spain
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	Universadad de Granada, Spain
	Stockholms Universite, Sweden
	Bilkent Universitesi Vakif, Turkey
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E. Postdoctoral Fellows

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Mohd Zeeshan
Dmitry Akhmetzyanov
Maryam Sadat Mirkamali
Roland Habluetzel Marrero
Michael Vasmer
Madelaine Liddy
Sarah McCarthy
Anirban Ch Narayan Chowdhury
Rubayet Al Maruf
Zheng Shi
Sasan Vosoogh-Grayli
Dogan Sinar
Yosri Ayadi
Simon Vallieres
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Ali Assem Abdelkader Mahmoud
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Bowen Yang
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Lin Tian
Jeremy Bejanin
Roksana Rashid
Katie McDonnell
Ernest Tan
Srijita Kundu
Hemant Katiyar
Tarun Patel
Jinglei Zhang
Fangchu Chen
Daozhi Shen
Adam Bene Watts
Ningping Cao
Fatemeh Fani Sani
Rui Yang
Dinesh Valluri
Gaili Wang
Pardis Sahafi

F. Graduate Students

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Aditya Jain	Emma (Annelise) Bergeron
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Nate Stemen	Bowen Yang
Maria Preciado Rivas	Paul Rev (Sung Eun) Oh
Kelly Wurtz	Andrew Cameron
Jose Polo Gomez	Erickson Tjoa
Adam Teixido-Bonfill	Nikhil Kotibhaskar

Einar Gabbassov	Sahand (Seyed) Tabatabaei
Eric Culf	Bharat Kuchhal
Yinchen (Calvin) Liu	Brendan Bramman
Tiasa Mondol	Evan Peters
Connor Paul-Paddock	Lane Gunderman
Samuel Winnick	Pei Jiang Low
Andrew Jena	Chung-You (Gilbert) Shih
Joan Etude Arrow	Noah Greenberg
Kohdai Kuroiwa	Xi Dai
Amolak Kalra	Kent Ueno
Li Liu	Shlok Nahar
Jesse Allister Kasian Elliott	Melissa Henderson
Rory Soiffer	Kimia Mohammadi
Vahid Reza Asadi	Annie Ray
Nizar Messaoudi	Roger (Xiuzhe) Luo
Brad Van Kasteren	Zachary Merino
Nikolay Videnov	Sayan Gangopadhyay
Cindy (Xinci) Yang	Pritam Priyadarsi
Jamal Busnaina	Elijah Durso-Sabina
Sai Sreesh Venuturumilli	Pablo Jaime Palacios Avila
Burak Tekcan	Bruno De Souza Leao Torres
Yu (Jerry) Shi	Devashish Jayant Tupkary
HeeBong Yang	Sriram Gopalakrishnan
He (Ricky) Ren	Omar Hussein
Rabiul Islam	Christopher (Xicheng) Xu
Rubaya Absar	Anastasiia Mashko
Gabriel Vinicius De Oliveira Silva	Anthony Vogliano
Anya Houk	Everett Patterson
Yawen Peng	Esha Swaroop
Matteo Pennacchietti	Cristina Rodriguez
Erfan Hosseini	Stephane Vinet
Abdolreza Pasharavesh	Nicholas Zutt
Guangyu Peng	Jae Jong Oh
Salehi Iman	Lars Kamin
Shayan Majidy	Sanchit Srivastava
Shazhou (Joey) Zhong	Sonell Malik
Kaveh Gharavi	Amir Arqand

Nachiket Sherlekar	Estevao De Oliveira
TC Fraser	Luke Neal
Jack Davis	Caroline De Lima Vargas Simoes
Matthew Duschenes	Forouzan Forouharmanesh
Benjamin Maclellan	Archishna Bhattacharyya
Yi Hong Teoh	Chi Zhang
Connor Kapahi	Reza Asadi
Noah Janzen	Adina Goldberg
Ejaaz Merali	Alec Gow
Stephen Harrigan	Padraig Daly
Paul Anderson	Yuming Zhao
Jiahui Chen	Kieran Mastel
Junan Lin	Jennifer Zhu

Master's Students

Adam Winick	Lucas Hak
Nicholas Olsen	Lemieux Wang
Darian McLaren	Richard (Lewis) Hahn
Alexandra Kirillova	Ilyas Sharif
Fiona Thompson	Xianfan Nie
Fangzhou Yin	Owen Lailey
Wenxue Zhang	Mohammad Ayyash
Camille Lacroix	Xiaoran (Nicole) Li
Dave Jepson	Aosheng (Michael) Gu
Mary Katherine MacPherson	Cheng Zhu
Xingyu Zhou	Justin Schrier
Natalie Parham	Brady Cunard
Sarah (Meng) Li	YiDan Zheng
Abrar Kazi	Xiaoxuan Fan
Zeyi Liu	Manar Naeem
Junqiao Lin	Anton (Tony) Lutsenko
Zhiying Yu	Kosar Shirinzadeh Dastgiri
Danny (Xiangzhou) Kong	Jack (John) Burniston
John (Can) Bostanci	Zachary Hinkle
Abhishek Anand	Mai Sakuragi
Tony (Anthony) Lau	Margie (Margaret) Christ

Pulkit Sinha	Artem Zhutov
Guofei (Phillip) Long	Maeve Wentland
Lucas Roy	Scott Johnstun
Ze Yuan (Michael) Li	Matthew Piatt
Sarah Odinotski	Victor Marton
Sathursan Kokilathasan	Satchel Jeanne Armena
Benjamin Jarvis-Frain	Olivia Woodman
Zhuoyang He	Rahul Menon
Marcel Robitaille	Collin Epstein
Jack DeGooyer	Arsalan Motamedi
Dhruv Gopalakrishnan	Amit Anand
Shaun (Shixin) Ren	Jingwen (Monica) Zhu
Yvette De Sereville	Parth Padia
Namanish Singh	Zhaoxin Zhang
Wilson Wu	Hawking (XingHe) Tan
Anthony Chytros	Noah Gorgichuk
Jacob Taylor	Xiao Yang
Albie Chan	Tristan Lismer
Olivier Nahman-Levesque	Andrija Paurevic
Paul Del Franco	Zachary (Zach) St Pierre
Alev Orfi	Megan Byres
Evan White	Tejas Naik
Ali Binai-Motlagh	Severyn Balaniuk

G. Invited Talks & Conference Participation

Faculty Member	Title/Subject	Institution/Conference
Michal Bajcsy	Single-photon source based on a quantum dot emitting at cesium wavelength	SPIE Photonics West On Demand: 01-02-22
	Manipulating single photons with atomic ensembles: tackling old challenges using nanophotonics	Quantum Days 2022: 08-02-22
	Nanophotonic platforms for quantum optics with atomic ensembles	CAP Congress: 01-06-22
Jon Baugh	Single-electron devices: applications to quantum information	Quantum-Nano collision series, Waterloo Institute for Nanotechnology (held virtually), June 10, 2022
Raffi Budakian	Nuclear Magnetic Resonance Diffraction (NMRd): A Probe of Structure and Dynamics of Spins at the Atomic Scale	University of Buffalo Physics Colloquium, Buffalo, 2022
	Angstrom-Scale Nuclear Magnetic Resonance Diffraction: A Route to Atomic Resolution Magnetic Resonance Imaging	Gordon Research Conference on Mechanical Systems in the Quantum Regime, Ventura, 2022
	Nuclear Magnetic Resonance Diffraction (NMRd): A Probe of Structure and Dynamics of Spins at the Atomic Scale	University of Rochester Physics Colloquium, Rochester
	Angstrom-Scale Nuclear Magnetic Resonance Diffraction: A Route to Atomic Resolution Magnetic Resonance Imaging	Nano MRI-7, Barcelona, Spain, 2022
Joseph Emerson	The Role of Randomized Compiling for Quantum Computing: from NISQ to QEC	SFB BeyondC'", Vienna, Austria, Sept 4-9 2022
David Gosset	Shallow circuits and the quantum-classical boundary	CIFAR Quantum Information Summer School, Quebec City, Canada, Sep 27, 2022
	Shallow Clifford circuits: quantum advantage and classical simulation	NSF workshop on quantum advantage and next steps, David Rubenstein Forum at the University of Chicago, Chicago, USA, August 1, 2022
	Classical algorithms for Forrelation	Los Alamos National Laboratory Summer School on Quantum Computing (online), June 23, 2022
	How to simulate measurement without computing marginals	Fifth Workshop on Algebraic Structures in Quantum Computing, University of British Columbia (online), June 14, 2022
Rajibul Islam	A brief journey of cold atomic physics: from clocks to quantum computers	Indian Association of Physics Teachers (Online) seminar to celebrate the National Science Day in India (28 Feb 2023)
	Simulating the quantum world with laser-cooled trapped ions	National Science Day seminar, IIT (ISM), Dhanbad, India (online) (14 Feb 2023)
	Trapped ion quantum simulation: opportunities and challenges	Colloquium, Indian Association for the Cultivation of Science, Kolkata, India (31 Jan 2023)

	A brief journey of cold atomic physics: from clocks to quantum computers	P. K. College, Contai, India (Online) seminar (17 Jan 2023)
	Trapped Ion Quantum Information Processing Effort at University of Waterloo	Cornell University (10 Oct 2022)
	Precise and programmable individual optical addressing for Yb+ and Ba+ qubits	North American Conference on Trapped Ions (NACTI), Duke University (01 Aug 2022)
	Site-selective dissipation and measurement without decohering neighbours in a static ion chain	ETH Zurich (19 July 2022)
	Probing coherent and dissipative dynamics on a trapped ion quantum simulator	WE-Heraeus-Seminar on Entropy and the Second Law of Thermodynamics, Physikzentrum, Bad Honnef/Germany (15 July 2022)
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	IISER Thiruvananthapuram (18 Apr 2022)
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	Purdue University (06 April 2022)
Alan Jamison	IP Involved Quantum Computing	Holland and Knight, Tampa, FLA, USA, January, 2023
	Quantum Coherent Chemistry with Ultracold Atoms and Molecules	Waterloo Chemical Physics Symposium, University of Waterloo, November 2022
	Laser Cooling to Quantum Chemistry	Institute for Quantum Computing, University of Waterloo, November 2022
	Laser Cooling to Quantum Chemistry	Institute for Quantum Computing, University of Waterloo, August 2022
	Quantum state control of ultracold chemistry	Cold Atom Molecule Interactions (CATMIN) Conference, Perimeter Institute, July 2022
Thomas Jennewein	QEYSSat – the Canadian quantum satellite mission	Universitat Innsbruck, 14/03/2023
	Advances for Satellite Quantum Communication Channels	Quantum 2.0 Conference and Exhibition, June 2022
	Keynote	Quantum Days conference, Jan 2023
	Transitioning Quantum Technologies to a Business	2022 CAP Conference, June 2022
	The quantum internet and why satellites will be needed	QIT46 Symposium, May 2022
	The quantum internet and why satellites will be needed	Photonics North, May 2022
	The quantum internet and why satellites will be needed	CLEO Space Optics Symposium, May 2022
Na Young Kim	Temperature Study of Rydberg Excitons in Cu2O	5th International Workshop on Rydberg Excitons in Semiconductors, 5/11/2022, Aarhus, Denmark
	Semiconductor Quantum Science and Technology Platforms	2022 the Association of Korean-Canadian Scientists and Engineers (AKCSE) Seminar Series, 10/6/2022
	Semiconductor Quantum Cavity QED Platforms: Bloch Exciton-Polaritons and Rydberg Excitons	2021 Quantum Week, 2021/6/27, South Korea - Virtual participation
	Solid-State Quantum Platforms: Bloch Exciton-Polaritons and Rydberg Excitons	Institute for Quantum Science and Technology Seminar, University of Calgary, 10/19/2022

	Hybrid Classical and Quantum Machine Learning Algorithms	2022 KOSEN Bridge Forum, 10/20/2022
	Solid-State Quantum Simulator Platforms	22nd Asian Quantum Information Science Conference, 12/18/2022
Raymond Laflamme	National Quantum Strategy Kick-off Meeting	Perimeter Institute, Waterloo, ON: 16-01-23
	Quantum Technologies	Quantum Days conference, Jan 2023
Debbie Leung	The platypus of the quantum channel zoo and their generic nonadditivity	CMS 2022 Winter Meeting, Toronto, Dec 2-5, 2022
Adrian Lupascu	Landau-Zener tunneling: from weak to strong environment coupling	1qbit seminar, Remote, March 17, 2023
	Landau-Zener tunneling: from weak to strong environment coupling	APS March Meeting, Las Vegas, US, March 6-10, 2023.
	Landau-Zener tunneling: from weak to strong environment coupling	International Network on Quantum Annealing conference, London, United Kingdom, November 9-11, 2022.
	Superconducting Qubits - Introduction and discussion of new research directions (tutorial)	6th International Workshop on Quantum Coherence, Control, & Computing, Center for Quantum Science and Engineering, Hoboken, New Jersey, October 12-14, 2022.
	The demonstration of switchable coupling between a two-level system and a waveguide implemented using superconducting systems	6th International Workshop on Quantum Coherence, Control, & Computing, Center for Quantum Science and Engineering, Hoboken, New Jersey, October 12-14, 2022.
	The demonstration of switchable detector-field coupling implemented using superconducting systems	Relativistic Quantum Information North, Waterloo, Canada, September 5th-9th, 2022.
Michele Mosca	Prosperity and resilience in the quantum era	International Quantum Conclave 2023, Centre for Development of Telematics(C-DOT), the telecom R&D centre of the Gov't of India, New Delhi, India (Hybrid), Mar 31, 2023
	National Quantum Strategy and Beyond: research and commercialization in Canada	Team Canada Booth, AAAS Annual meeting, Science for Humanity, Washington, USA, Mar 4, 2023
	Toward a more resilient quantum future	AAAS Annual meeting, Science for Humanity, Washington, USA, Mar 4, 2023
	Emerging technologies	Research Security Conference, Research Security in Today's Geo-Political Era, Federation Hall, University of Waterloo, ON., Feb 7, 2023
	Entering the Quantum Era	Board Excellence Digital Edge Monthly Call, Jan 11, 2023, (virtual)
	Quantum Computing: Opportunities and Risks	Rotman Event, University of Toronto, Toronto, Canada, Nov 22, 2022
	CEO Roundtable with Vivek and Dominic Barton	"Technology Disruptions" University of Waterloo, Waterloo, Canada, Nov 22, 2022, (virtual)
	Quantum computer and quantum attacks	Blackberry Innovation Technology Series Talk, (Virtual), Nov 15, 2022
	Who will use them and when	Inside Quantum Technology, New York city, USA, Oct 25, 2022

	Preparing for the Post-Quantum Era of cryptography	FinCyber Today" summit, Scottsdale, AZ, USA, hosted by FS-ISAC, Oct 12, 2022
	Quantum Computing and AI	AI and Electric Power Summit, Rome, Italy, Oct 4-6, 2022
	Quantum Technologies in Defence and Intelligence Security	special expert briefing event at DND/CAF on the implications of quantum technology on intelligence, September 20, 2022 (virtual)
	Toward cybersecurity in the quantum era	SWIFT Institute staff training on Quantum Computing and its potential for the Financial Industry, September 22, 2022 (virtual)
	Panel Discussion: Now what? Changes in the post-quantum ecosystem	International Cryptographic Module Conference (ICMC2022) Virginia, USA, September 15, 2022
	CISA Secure Tomorrow Series: Scenarios Workshop	CISA's National Risk Management Center (NRMC), Boston, USA, August 17/18, 2022
	A review of NIST post-quantum standardization project	Glowing Hot Topics in Cryptography (GHTC): Cryptographic Agility, University of California, Santa Barbara, affiliated event of Crypto2022, August 13, 2022
	Strategic Outlook on the future of Quantum Computing	World Economic Forum' Global Technology Governance Retreat 2022, San Francisco, United States, June 23, 2022
	Creating the Quantum Industry, what it takes to Found, Fund and Run a Startup?	Quantum 2.0 conference and Exhibition, June 15, 2022
	Quantum opportunities and Risk	BX Digital Edge, Hathaway Global Strategies, LLC, June 14, 2022
	Quantum Key Distribution vs. Post Quantum Cryptography vs. TrUE Quantum Encryption: Who is the Betamax, who is the VCR, and who is the DVD?	QT Quantum Tech, Boston, United States, June 14, 2022
	Data Privacy and Insurance in the Quantum Age	10th Annual Forum on Canadian Cybersecurity Forum, Cambridge, Canada, May 30, 2022
	Post-quantum cryptography	Entrust Engaged Podcast, May 27, 2022 (Virtual)
	Will we see unintended consequences from quantum? How do we mitigate risk with dual technologies?"	Commercializing Quantum, Economist Impact, United Kingdom, May 19, 2022 (virtual)
	Cybersecurity and Quantum Computing	Toronto Youth Stem and Innovation Conference, April 23, 2022, (virtual)
	Quantum 101	Confronting the Quantum Challenge: Business Innovation Technology Security (BITS) Quantum Computing Symposium, April 21, 2022, (virtual)
Christine Muschik	Next Challenges in Quantum Simulation	APS, Las Vegas, NV, March 5 -10 2023
	Simulating Particle Physics with Quantum Computers	Synthetic Intelligence Forum – Virtual Dec 19th, Toronto, ON
	Quantum chromodynamics	Leiden University, Netherlands, Dec 14th, 2022 virtual
	TQT Scientific Advisory Council Meeting	October 2022, Waterloo, ON
	Quantum Information Science (QIS) Program	CIFAR Sept 27 2022, Quebec, QC
	Teaching Quantum Computers to Simulate Particle Physics	Centre for Quantum Information and Quantum Control (CQIQC IX) Toronto, ON, August, 2022

	Fresh Approaches to Quantum Computing	Presentation to Perimeter Institute at Board Meeting, Waterloo, ON, June 2022
	Teaching quantum computers to simulate gauge theories for particle physics	Canadian Association of Physicists (CAP) Congress, McMaster University, Hamilton, ON June 2022
Ashwin Nayak	Applications of the information-theoretic method in quantum computation	10th Iran Workshop on Communication and Information Theory, online, Iran, May 11, 2022
	Bounds on Sample Complexity via Information Theory. Thematic semester: "Symmetries: Algebras and Physics	Algebraic Combinatorics and Mathematical Physics; Centre, de recherches mathématiques (CRM), Montreal, QC, Canada. The semester series ran from May to Dec 2022.
Dmitry Pushin	Neutron Interferometry and structured waves of matter and light	Quantum Information Seminar, University of Toronto, Canada, 2023
	Neutron Interferometry for Metrology	QSQS 2022, University of Washington, USA, 2022
	Integrating structured wave techniques into neutron sciences	ICOAM 2022, Tampere, Finland, 2022
	Neutron Interferometry and Current Advance	ACNS 2022, University of Colorado, Boulder, Colorado, USA, 2022
Micheal Reimer	On-demand III-V quantum light sources	NSERC CREATE BC- CMC Quantum Photonics Workshop, February 20 – 24, Vancouver, Canada, 2023
	Near-term Applications of Quantum Sensing Technologies in Biomedical Sciences	NIH Virtual Workshop, January 5-6, 2023
	Quantum nanophotonic devices for quantum computing, communication, and sensing	The Annual Conference of the IEEE Photonics Society, November 13 – 17, Vancouver, Canada, 2022
	Photonic nanowire quantum devices	Seminar, May 31, NIST, Online, United States, 2022
	On-demand generation of entangled photon pairs with near-unity fidelity	Photonics for Quantum 2022, June 6 – 9, Rochester, United States, 2022
	Solid-state quantum sensors for biomedical imaging	Seminar, May 6, NIST, Online, United States, 2022
	On-demand generation of entangled photon pairs	Photonics North 2022, Niagara Falls, Canada, 2022
Crystal Senko		American Physical Society (APS) Division of Atomic, Molecular, and Optical Physics (DAMOP) annual meeting, June 2022, Orlando, FL
		APS DAMOP graduate student symposium, June 2022, Orlando, FL
		North American Conference on Trapped Ions (NACTI), August 2022, Durham, NC
	Quantum Processors	Quantum Days conference, Jan 2023
		Canadian Graduate Quantum Conference, Jan 2023
William Slofstra	Bell inequalities and decision problems in C*-algebras	Wales MPPM Mathematical Physics-Physical Mathematics Seminar (on- line) , October 2022
	Positivity Is Undecidable in Tensor Products of Free Algebras	MTNS 2022, Bayreuth, Germany (talk given online), September 2022
	MIP*=RE: what it is and further directions for operator algebraists.	MFO, Oberwolfach workshop on C*-algebras, August 2022

	Positivity and sums of squares in products of free algebras	Tutte Colloquium, University of Waterloo, July 2022
	The non- commutative geometry of quantum correlation sets: from Tsirelson to now	Tsirelson Memorial workshop, IQOQI Vienna (talk given online), April 2022
Adam Wei Tsen	Tunneling Probe of Magnons in 2D Alpha-RuCl3	American Physical Society March Meeting, Las Vegas, NV, Mar.8, 2023
	Tunneling Probe of 2D Kitaev and Moiré Magnetism	Department of Physics Colloquium, Wake Forest University, Feb.16, 2023
	Tunneling Probe of 2D Kitaev and Moiré Magnetism	Quantum Matters Seminar, University of Waterloo, Jan.18, 2023
	2D Heterostructures for Broadband Photodetection and Spectroscopy Beyond the Diffraction Limit	International Workshop on Quantum Circuits in 2D Materials, University of Ottawa May 27,2022
	Tunneling Probe of Two-Dimensional Magnetism	Department of Materials Science and Engineering Seminar, University of Wisconsin, Madison Apr.14, 2022
Guo-Xing Miao	Spin Manipulation with Ionic Motion in Solid State Systems	Beijing Academy of Quantum Information Sciences, Beijing China, Aug. 2022
Chris Wilson	Analog Quantum Simulation of Topological Models	Quantum Information Science for Nuclear Physics, Santa Fe, New Mexico, January 31, 2023.
	Generating Quantum Microwaves using Superconducting Circuits	SNOLab Colloquium, Sudbury, Canada, 2022
	Analog Quantum Simulation of Topological Models with a Parametric Cavity	Quantum Microwaves, Heat Transfer and Many-Body Physics in Superconducting Devices, Trieste, Italy, 2022
Jon Yard	Arithmetic of quantum circuits and SIC-POVMs	FoQaCiA kickoff meeting, Nov 3, 2022

H. Scientific Visitors & Tours

Visitor Name	Visitor Affiliation
Oliver Morin	Max Planck Institute of Quantum Optics, Germany
Dimitrios Antsos	NASA Jet Propulsion Laboratory
Alexander Lohrmann	NASA Jet Propulsion Laboratory
Makan Mohageg	NASA Jet Propulsion Laboratory
Matt Shaw	Jet Propulsion Laboratory
Andy Schang	Cornell University
Ana Bershanska	University of Toronto
Meliza Ozen	University of Ottawa
Fabien Lefebvre	University of Ottawa
Ana Bershanska	University of Toronto
Akimasa Ihara	Cornell University

Hyo Sun Park	Bryn Mawr College
Tian Ooi	University of Alberta
Craig Colquhoun	Craft Prospect Ltd
Xuedong Hu	University of Buffalo
Phillip Kaye	National Research Council Canada
SeongMin CHo	Hanyang University Korea
Gyuseop Lee	Hanyang University Korea
Seung-Hyun Seo	Hanyang University Korea
Nayeli Azucena Rodriguez-Briones	University of California, Berkeley
Pasha Shavelev	Queen's University, Kingston
Dillion Cottrill	Stony Brook University
Maris Ozols	UNIVERSITY OF AMSTERDAM QuSoft
Anupam Mazumdar	University of Groningen
Stephanie Simmons	Simon Fraser University
Cihan Okay	Bilkent University, Turkey
Rodolfo Reis Soldati	University of Stuttgart
Lianao Wu	University of the Basque Country UPV / EHU
Mario Szegedy	Rutgers University
Chinmay Nirkhe	IBM Research
Richard Germond	Queen's University, Kingston
Hyeung Joo Lee	Korea Institute for Advanced Study (KIAS)
Jaewan Kim	Korea Institute for Advanced Study (KIAS)
Won Hyeong Choi	Korea Institute for Advanced Study (KIAS)
Ahmad Farooq	Kyung Hee University
Ali Assem Abdelkader Mahmoud	Perimeter Institute
Stephen Vintskevich	University of Moscow (formerly)
Joshua Montgomery	tO.technology
Amir Raeesi	Qubic, Inc
Jean-Philippe Bourgoin	Single Quantum Systems
Giampiero Marchegiani	Technology Innovation Institute, Abu Dhabi
Michael Hilke	McGill University
Tony Leggett	University of Illinois at Urbana-Champaign
Dominik Hangleiter	University of Maryland

Richard Curry	The University of Manchester
Ewin Tang	University of Washington
Alessandro Serafin	Bluefores Inc.
Stacey Jeffery	QuSoft, Research Centre for Quantum Software, The Netherlands
Henri Morin	University of Ottawa
Jonathan Lavoie	Xanadu Quantum Technologies
Sushil Majumdar	Tata Institute of Fundamental Research
Harold Ollivier	French National Institute for Research in Digital Science and Technology
Felix Motzoi	Stadt Julich
Zachary Mann	University of Montreal
Jerry Li	Microsoft Research
Hector Spencer-Wood	University of Glasgow
Sarah Croke	University of Glasgow
Alessandro Serafin	Bluefores Inc.
Carlos Perez Delgado	Kent University
Claude Crepeau	McGill University
Sumeet Khatri	Freie Universitat Berlin
Julien Laurat	Kastler Brossel Laboratory, Paris
Yusif Akhund	Lockheed Martin
Zolzaya Erdenebileg	Qubic Technologies, Inc
Jerome Bourassa	Qubic Technologies, Inc
Jack Winters	Lockheed Martin
Brian Mason	Lockheed Martin
Thomas Loftus	Lockheed Martin
Sanipa Arnold	Lockheed Martin
Eric Culf	University of Ottawa
Urbasi Sinha	Raman Research Institute
Ojas Parekh	Sandia National Laboratories
Ben Criger	Cambridge Quantum Computing
Urbasi Sinha	Raman Research Institute
Bhaskaran Muralidharan	Indian Institute of Technology Bombay
Zhaoyi Li	Stanford University
Sougato Bose	University College London

Alexander Pickston	Institute of Photonics and Quantum Sciences, Heriot-Watt University, UK
Xiao Mi	Google
Shawn Ren	N/A
Katanya Kuntz	University of New South Wales, Canberra, Australia
Nikola Sarah Mang	Technical University Dortmund
Anaida Ali	Indian Institute of Technology, Bombay
Hope Fu	Massachusetts Institute of Technology
Smita Rajan	Brown University
Angus Russell	University of Strathclyde
Hyo Sun Park	Bryn Mawr College
Michael Liu	Amherst College
Emiliia Dyrenkova	University of California, Berkeley
Keshav Adhyay Rakesh	University of Illinois at Urbana-Champaign
Rohan Joshi	Delhi Technological University, Delhi, India
Aleksander Kubica	California Institute of Technology
Edgar Solomonik	University of Illinois at Urbana-Champaign
Mahadevan Subramanian	Indian Institute of Technology, Bombay
Marcin Kepa	University of Warsaw
Christoforos Iakovou	University of Strathclyde, Glascow
Vladyslav Los	Ludwig Maximilian University Munich
Graeme Smith	University of Colorado, Boulder
Philippe Faist	Free University of Berlin
Zolzaya Erdenebileg	Qubic Technologies, Inc
Jerome Bourassa	Qubic Technologies, Inc
Gregory Rosenthal	University of Toronto