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**For submission to the Ministry of Innovation, Science and
Economic Development
July 31, 2021**





FROM THE EXECUTIVE DIRECTOR

From IQC's Newly Appointed Interim Executive Director

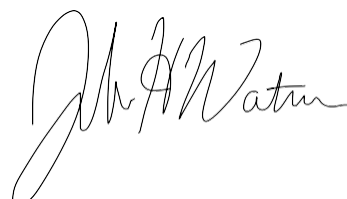
Fiscal 2020-2021 was a year of transformation. The Institute for Quantum Computing (IQC) persevered through the unprecedented pandemic, overcoming challenges and strategically shifting strategies to ensure ongoing success. The impact of IQC over the last year highlights the power of sustained commitment and collective efforts to build something truly unique right here in Canada. 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 the global knowledge with 170 published papers, 124 presentations and 113 ongoing collaborations, \$4.6M in earned media and 73 outreach initiatives reaching 11,800+ people. Our graduate program attracted 197 students from across the country and around the world, and we prepared to launch the first year of our new course-based master's program, tailored to industry professionals, this coming fall. Additionally, we welcomed 17 new postdoctoral fellows, and 7 new research associates. In our three locations (the Mike and Ophelia Lazaridis Quantum-Nano Centre, and the two Research Advancement Centre buildings), labs are continuing to be outfitted as the field advances and new researchers join our growing community.

IQC is advancing the field of quantum information to discover and commercialize powerful new technologies that will play a transformational role in providing us with extraordinary levels of efficiency, security and precision. We are proud that the research and innovations at IQC are spinning out into new companies and building a connected community of academic and industry R&D activities right here in Canada.

As IQC's newly appointed Interim Executive Director and IQC faculty member since 2005, I look forward to continuing this journey of innovation along with the Government of Canada. Thank you for your continued support.

Sincerely,



John Watrous
Interim Executive Director, Institute for Quantum Computing
Professor, School of Computer Science
University of Waterloo



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EXECUTIVE SUMMARY

Significant progress has been made in quantum information and technology over the past twenty years and today we are seeing firsthand how quantum information research leads to the discovery and engineering of systems with capabilities far beyond those that previously existed. Since its founding in 2002, IQC has become an engine driving the creation of knowledge and technology in quantum information and is sparking commercialization initiatives that will benefit Canadians today and far in the future. IQC remains a key driver of Canada's emerging quantum economy.

In support of its important work, in 2019 IQC was awarded \$15M in funding to be used over three years by the Government of Canada. This funding will serve to support five key objectives and the great strides IQC has made on each of them.

Highlights from the 2020-2021 year, include:

- Attracted over \$30,000,000 in funding
- Recruited one new Research Assistant Professor and seven research associates
- Welcomed 17 new postdoctoral fellows
- Published 170 papers in peer-reviewed journals
- Reached over 62,000 cumulative citations
- Delivered presentations to more than 120 academic peer groups across Canada and the globe with more than 110 ongoing collaborations
- Attracted 425+ applications from across Canada and the world to graduate programs, including 20% from women
- Over 450 awards received by IQC graduate students
- Hosted one workshop, 34 seminars and 10 colloquia, and sponsored 4 external scientific programs
- Engaged over 11,800 people across diverse audiences, increasing awareness and understanding of quantum through 70 scientific outreach initiatives
- Developed a new course-based master's program, tailored to developing industry professionals that will launch in Fall 2021

With its partners, IQC is building Canada's quantum information economy in Waterloo. IQC has leveraged its world-leading infrastructure and outstanding scientific capability to build Canada's first market-facing environment for designing, building and testing quantum information services and devices. As IQC continues its rapid growth and advances the understanding of the quantum world, Waterloo Region's – and Canada's – reputation as a world leader in quantum will continue to be solidified.



INSTITUTE FOR QUANTUM COMPUTING

The Institute for Quantum Computing (IQC) at the University of Waterloo was founded in 2002 to seize the potential of quantum information science for Canada. IQC's vision 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 come to IQC to conduct research, share knowledge and encourage the next generation of scientists.

IQC is leading the next great Canadian technological revolution – the quantum revolution. Quantum technologies and applications developed in IQC labs create 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, the Government of Ontario and the University of Waterloo. This strategic private-public partnership has accelerated the advancement of quantum information research and discovery, not only in Canada, but 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 in 2008:

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

2019-2022

In 2019, IQC was awarded \$15M over three years from the Government of Canada in support of the following five objectives:

- A. Increase knowledge in the various fields and sub-fields of quantum information, thereby positioning Canadians at the leading edge of quantum information research and technology;
- B. Create new opportunities for students to learn and to apply new knowledge to the benefit of Canada, spurring innovation, and investment in R&D activities through highly qualified personnel development;
- C. Brand Canada as the destination of choice for conducting research in quantum technologies and attract the best in the world to Canada, creating partnerships with the international quantum information community and promoting a world-class excellence in quantum information science and technology;
- D. Enhance and expand the Institute's public education and outreach activities to effectively promote science and quantum information science and demonstrate how the research from quantum information science can be applied for the purpose of sustaining and attracting world class talent;
- E. Increase translating research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada, thereby enhancing partnerships and collaborations with private sector partners and commercialization opportunities.

Through the activities planned and undertaken with the contribution of the Government of Canada in the past years, IQC has positioned Canada to take full advantage of socioeconomic benefits of quantum research and technology. What follows is progress achieved in the 2020-2021 year.



ACHIEVEMENTS 2020-21

Objective A

Increase knowledge in the various fields and sub-fields of quantum information, thereby positioning Canadians at the leading edge of quantum information research and technology.

Expected Result: Increase knowledge in quantum information and technology.

Planned Activities:

- Leveraging talent from across three University of Waterloo Faculties—Science, Mathematics and Engineering—researchers will continue IQC’s collaborative and interdisciplinary research agenda in quantum computation, quantum communication, quantum sensors and quantum materials
- Publishing research results in world-leading journals
- Recruiting new faculty members, research assistant professors and research associates
- Continuing to outfit labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre as new IQC members are recruited
- Continuing to outfit and maintain the Quantum Nano Fabrication and Characterization Facility to enable fabrication of quantum-enabled technologies
- Updating and maintaining of lab space in the Research Advancement Centre 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 & Citations

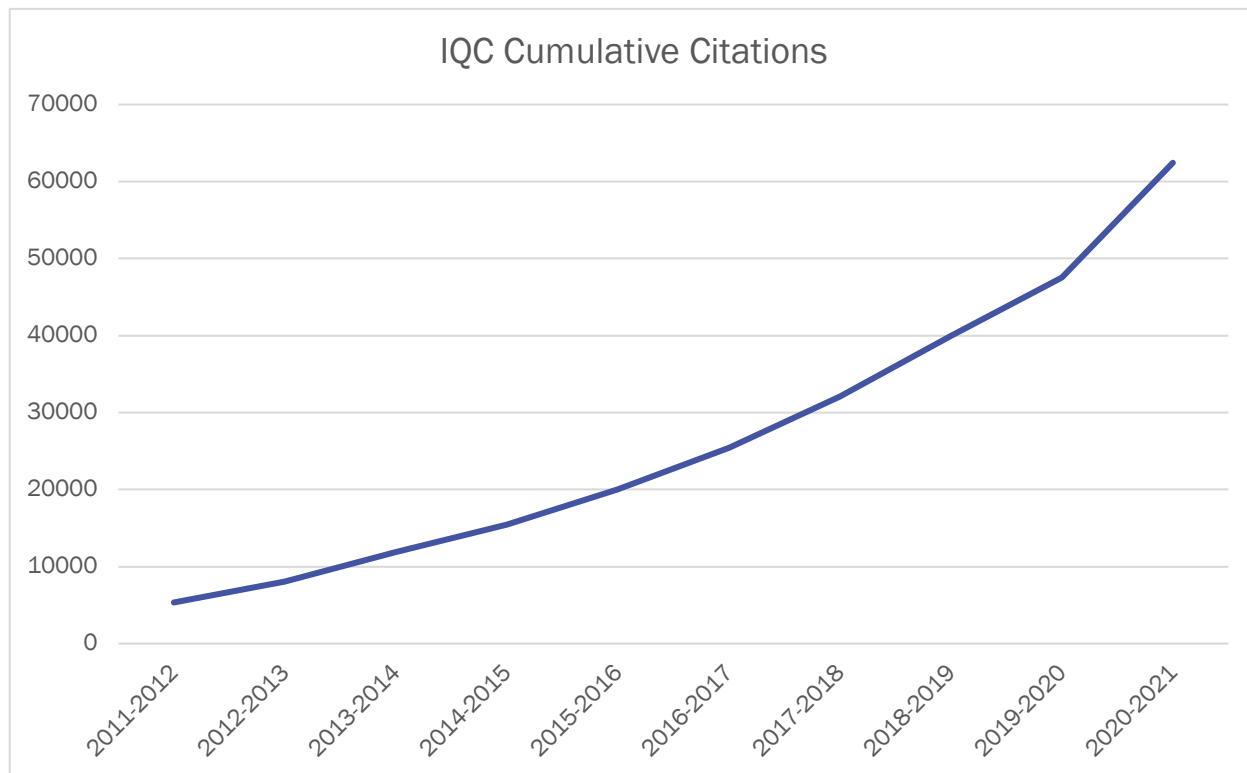
In 2020-2021, IQC researchers collectively published 170 papers in peer-reviewed journals bringing the cumulative number of publications to 2431¹ since 2002. Several papers appear in prominent scientific publications including Science, the Nature family, the Journal of Mathematical Physics and Physical Review Letters. Below is a summary of articles published in prominent journals since 2014. A full list of all papers published this year can be found in Appendix B beginning on page 60.

Prominent Publications	14-15	15-16	16-17	17-18	18-19	19-20	20-21
Family of Nature Journals	11	7	9	9	4	9	12
Physical Review Letters	26	17	11	6	8	15	8
Science	1				1		
Journal of Mathematical Physics	5	7	3	4	5	1	3
FOCSs	2	2	1			9	1
STOC	3	1	2	1	1	1	3

Further analysis reveals that 67% of IQC papers (from 2002 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, Tsinghua University, Université de Sherbrooke, University of British Columbia and University of Toronto.

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 the research published. As of March 31, 2021, the number of cumulative citations from IQC's published papers reached 62,437. The growth chart below highlights the large increases in IQC citations given the moderate faculty growth, highlighting the high impact of IQC researchers.



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 2010-2021. Data pulled on March 31st of each fiscal year.

Research Highlights


The following stories are only a sample of the research published at IQC over the last year. These stories serve to highlight the breadth and depth of the research coming from the Institute.

FINDING THE GROUND STATE OF SPIN HAMILTONIANS WITH REINFORCEMENT

Published in Nature Machine Intelligence on September 7, 2020

<https://www.nature.com/articles/s42256-020-0226-x>

Advanced simulations may one day be able to help us explore new frontiers in atomic physics, build new materials and discover new drugs. But first, researchers must find the best ways to control these simulations. New research featured on the cover of Nature Machine Intelligence explores machine learning as a method for achieving optimal control.



Pooya Ronagh, Research Assistant Professor at IQC and the Department of Physics and Astronomy, demonstrated that a machine learning program can be trained to find the best ways to control systems it has never interacted with before.

“When people learn how to play one Atari game, we learn a lot about how to play every Atari game,” said Ronagh. “Right now, machine learning models need to be trained on each game separately. But what we really want is for them to be able to play the next game they have never seen before right off the bat.”

Ronagh’s team, which included Kyle Mills and Isaac Tamblyn of the Ontario Tech University and the National Research Council of Canada, simulated systems made up of particles. They wanted to control the temperature of these systems from hot—high energy—to cold—low energy, also known as the ground state. More specifically, they wanted to see if a type of machine learning called reinforcement learning could find the optimal schedule for dialing down the temperature in different system arrangements.

Reinforcement learning is a type of machine learning where a program learns how to best achieve a desired outcome by repeatedly interacting with a changing system. Regular temperature control schedules use analytic formulae. But the team found out that reinforcement learning can find highly irregular but better control schedules, especially when simulation is done on a much larger system.


The researchers’ program evolved a particle system from hot to cold repeatedly in a process of trial and error. After this period of training, the program was able to find improved control schedules on brand new systems it had never experienced. The program’s ability to find these schedules scaled well with the size of the system. Ronagh said that this performance is a promising start for using reinforcement learning for quantum control.

“The ultimate agenda is to build a good quantum computer, and for that, we need good qubits,” said Ronagh. “To build good qubits, you need to simulate the physics. You need to be able to control the evolution the system goes through.”

With its promising initial performance, Ronagh now hopes to extend the reinforcement learning technique to the quantum realm.

The team already started in this direction by making use of “destructive” measurements. To evolve the system from hot to cold, the control program needs to take temperature measurements along the way. However, taking measurements of a quantum system alters how it evolves. To test their program on quasi-quantum systems, the team instructed it to restart every time it took a measurement, emulating the destructive results of measuring a quantum system. They still achieved an improvement in scalability, suggesting reinforcement learning may be an effective method of quantum control.

And quantum control isn’t just useful for qubits. “At a higher level, many quantum algorithms simulate physical evolutions, and the performance of the algorithm depends upon the choice of these evolutions,” said Ronagh. “The reason drug discovery is so expensive is they have to make something, test it, and then throw it out and try a new



mixture. What if I could simulate the drug and understand its properties with a quantum processor?”

To do that, researchers would need to run an algorithm that models the physics of the drug. “That in itself is an evolution. I must be able to control that evolution so that I get to the state of the drug that is the steady state seen in nature. The question is, what is the best way to achieve optimal quantum control? Machine learning is an exciting possibility.”

IMPLEMENTATION OF A WALSH-HADAMARD GATE IN A SUPERCONDUCTING QUTRIT

Published in Physical Review Letters on October 27, 2020

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.180504>

Researchers have implemented a gate used in important quantum algorithms in one step on a three-level quantum system—a qutrit—for the first time.

The new work led by Ali Yurtalan, Research Associate at IQC and in the University of Waterloo Department of Physics and Astronomy, identifies and addresses key challenges to controlling a qutrit, bringing researchers one step closer to developing quantum computers based on these multi-level quantum processors.

In computing, a gate is a logical operation that processes inputs to generate an output. In a classical computer, a gate returns a 0 or a 1. A gate implemented on a qubit—a quantum bit—returns a 0, 1, or some superposition of those possibilities. A gate implemented on a qutrit has many more possible outputs, including a 0, 1, 2, or some superposition between any or all these states.


An extra level in each processing unit of a computer means a lot more options for implementing existing quantum algorithms and developing new ones. It also opens the possibility of quantum processors that process information with two levels like a qubit but use the third level of a qutrit to help with things like error correction.

But adding another level to a system doesn’t just add capability. It also adds complexity.

“There are challenges when you’re addressing a qutrit,” said Yurtalan. “When you try to control all three levels of the system at the same time, there are going to be shifts to the energy levels of the qutrit.”

The researchers, working with faculty member Sahel Ashhab of Hamad Bin Khalifa University, were able to identify and characterize the shifts of the energy levels in their superconducting qutrit. They then dynamically compensated for these shifts while they implemented their gate across all three levels of the qutrit with one microwave pulse.

“We’ve identified the natural challenges that will arise when trying to control these qutrits, and we identified how to address them,” said Yurtalan. “This understanding will hopefully help us generalize our gate implementation to systems with more than three levels.”



The gate that the team implemented is common to many critical quantum algorithms that will have powerful capabilities once there are quantum computers powerful and stable enough to run them. And while the gate is just one small part of any given algorithm, Yurtalan is hopeful that this work is a step towards control of powerful quantum computers made up of qudits, the general term for quantum systems with three or more levels.

“Implementing this gate is a step towards implementing critical quantum algorithms, so this development is another small step towards useful quantum computation.”

The superconducting qutrit the researchers implemented their gate on was also the object of research for the latest IQC Achievement Award winner, Michal Kononenko, also an author on this paper.

EFFICIENT LEARNING OF QUANTUM NOISE

Published in Nature Physics on August 10, 2020

<https://www.nature.com/articles/s41567-020-0992-8>

Quantum computers will now have help tackling the central problem in their performance – noise.

Joel Wallman, a researcher at IQC and assistant professor of applied mathematics at the University of Waterloo, has developed a protocol that will help deal with the issue of noise in quantum computers so that they can tackle more complex problems.

“The intrinsic noise in quantum computers makes their output unreliable,” said Wallman, co-founder of Quantum Benchmark, a startup spun out of IQC. “So any problem that we know how to solve on a quantum computer can be solved better on conventional computers. To deliver quantum computers that can do something useful, we need to make larger quantum computers and work out how to accurately control them.”

Wallman, together with Robin Harper and Steve Flammia of the University of Sydney, has developed a new protocol that works on large systems – quantum computers running on many qubits (the quantum version of a classical computer’s binary bit)– that lets researchers characterize quantum noise across the qubits reliably and efficiently.

Prior to this work, researchers ran error assessment protocols that could only detect errors on a small subset of the qubits. The new method returns an estimate of the effective noise and can detect error correlations within arbitrary sets of qubits.

“The reason this protocol is so important is that if noise in systems don’t act locally, existing error correction and mitigation techniques just don’t work,” says Wallman. “And the data we obtained demonstrated that such nonlocal errors exist in real quantum computers.”

Wallman’s research team at the University of Waterloo and Quantum Benchmark is currently furthering the technique to characterize and suppress errors in specific data operations.



Tools based on the method are included in True-Q, the world-leading error characterization software from Quantum Benchmark.

MACHINE LEARNING DESIGN OF A TRAPPED-ION QUANTUM SPIN SIMULATOR

Published in Quantum Science and Technology January 21, 2020

<https://iopscience.iop.org/article/10.1088/2058-9565/ab657a>

“In the future, I don’t think this is going to be replaced with a quantum computer,” said Rajibul Islam, faculty member at IQC and the Department of Physics and Astronomy, as he pointed towards his desktop computer.

Instead, Islam sees classical computers like the one on his desk working together with quantum computers to solve problems currently impossible with classical computers alone. Thanks to new research, Islam thinks trained neural networks—classical machine learning systems that have ‘learned’ to solve a problem by analysing examples—could play an important role in this hybrid future.

Islam, in collaboration with Roger Melko, IQC affiliate and faculty member in the physics and astronomy department, has demonstrated that a trained neural network can quickly determine the right setup to run a given quantum simulation, a step toward classical-quantum hybrid computers that will tackle the hardest problems of physics and materials science.

Easy in, not so easy out


There is a broad set of problems that appear in almost every area of computation called inverse problems that are trivial to solve in one direction but extremely difficult to solve in the opposite direction. Experimentalists trying to simulate a quantum system on a trapped ion quantum simulator run into an inverse problem.

By setting the parameters of their simulator—like laser frequency and intensity—it is simple to solve an equation and determine what interaction is being reproduced in the simulator with those parameters. However, if researchers want to figure out how to set their lasers in order to simulate a specific quantum interaction, like the interaction of electrons in a quantum material, a classical computer must crunch numbers, sometimes for hours for a large system, for each desired interaction.

Once Islam and Melko realized that this problem is really an inverse problem, they had an idea. What if they could train a neural network to recognize a pattern between the experimental parameters and the trapped ion interactions? There was no way to know if it would work without trying. They put two Waterloo undergraduate students, Marina Drygala and Yi Hong Teoh, to work on the problem.

Testing an idea

Yi Hong and Marina found that the neural network, trained with thousands upon thousands of synthesized parameters and resulting interactions, converged on a pattern between them.



Though the training can take hours or days depending on the size of trapped ion system, once trained, a standard desktop computer can return the correct experimental parameters needed to simulate a specific quantum interaction in less than a millisecond. Moreover, since the problem the neural network is solving is an inverse problem, it is trivial to check that the results are accurate once the hard work is done.

“This inverse problem can be applied to so many different problems in quantum computing,” said Islam. “If you look at very complicated ion chips used by companies like Honeywell and IonQ, they have basically the same problem with voltages and the electrical potential applied to their ions.”

Islam is hopeful that more applications for this machine learning approach will surface, and that quantum computers augmented by machine learning will one day tackle the hardest problems in physics and materials science.

“I think the future of quantum computing will combine the strengths of classical computation like machine learning and the strengths of quantum to solve problems that are very hard for either alone. This result is a great step in that direction.”

QUANTUM ADVANTAGE WITH NOISY SHALLOW CIRCUITS

Published in Nature Physics, July 06, 2020

<https://www.nature.com/articles/s41567-020-0948-z>


New research shows that limited near-term quantum computers may be more powerful than they seem when solving a problem that is impossible for comparable classical computers.

Collaborators from the IQC, IBM, Technical University of Munich, and the University of Technology Sydney created an algorithm to solve a problem on a noisy quantum circuit that has a constant depth, meaning it has to solve the problem within a set upper limit of steps.

“We’re interested in constant-depth circuits because the kind of near-term quantum computers being built accumulate more errors the longer they operate,” said David Gosset, faculty member at IQC and in the Department of Combinatorics and Optimization at Waterloo’s Faculty of Math. “So, we want to look at restricted models of quantum computing that make the most of the ‘quantumness’ with the least computation.”

Correcting for errors caused by noise in a quantum circuit normally takes extra steps, losing the quantum advantage of solving the problem in a limited amount of time. The algorithm the researchers created corrects for errors at the same time as it solves the problem, allowing the circuit to remain constant depth. There is no classical algorithm that can solve the same problem using a constant-depth circuit, even one that is noise free. As the inputs into the problem grow, the classical circuit needs to grow logarithmically.

Think of it like driving a racetrack that is a set length, but the slope of the track keeps rising as you race. A quantum car—the researchers’ new algorithm—can keep on going,



even dodging potholes along the way. A classical car will need to be tuned with more and more power as the slope increases, even with a perfect road.

The algorithm may be implementable in the future with quantum computers that are able to perform some of the basic elements of quantum error correction.

The quantum computers scientists will be able to build in the short-term will be very limited and noisy. If theoreticians develop better algorithms that can solve problems on a quantum circuit in a very small number of steps, then better results will be possible with these near-term quantum computers.

“The problem we’re solving with the circuit is not necessarily useful itself, but the fact that there is a quantum advantage is another piece of evidence that quantum computers may one day be able to surpass classical computers at certain tasks,” said Gosset.

ACHIEVING THE ULTIMATE QUANTUM TIMING RESOLUTION

Published in PRX Quantum: A Physical Review Journal January 4, 2021

<https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.2.010301>

The precise measurement of time delays and colour differences is the core of many modern technologies, including spectroscopy and radar. Research conducted by John Donohue, Senior Manager of Scientific Outreach IQC, is using quantum-inspired techniques to achieve a new level of precision of measurement.


Donohue was working as a postdoctoral fellow in Professor Christine Silberhorn's Integrated Quantum Optics group at Paderborn University in Germany from 2017 to 2018. The research team, along with collaborators from Palacký University and the Complutense University of Madrid, have demonstrated a new method for measuring and characterizing pulses of light in time with improved precision.

The key to their technique is a homegrown waveguide device called a quantum pulse gate, developed at Paderborn University. This small chip contains and guides light like an optical fibre but has some rather grand capabilities beyond that.

When a laser beam is focused to a small point, it quickly expands back to its original size. By trapping it in a waveguide, laser beams and photons can be tightly focused down to a few millionths of a metre wide and kept that way for a few centimetres.

"Effects that might be difficult to explore by focusing into crystals and other optics become much more efficient and easier to explore (with the waveguides)," Donohue says.

Where physically measuring the distance between two objects is not possible, like stars in space, we must infer it in an indirect way. One way to infer and estimate how far apart two objects or signals are by using an optical timing measurement to detect pulses of light. However, this can be incredibly difficult to do if those pulses don't share coherence.



"If two pulses are so close together that they bleed into each other, I can't easily separate which is which. I'd need a ton of information to precisely answer the simple problem of how much time is between them," Donohue says. "In quantum language, to get more information, we need to measure more photons. So how can we get this information while measuring as few photons as possible?"

Donohue knows that with a different set of measurements, inspired by quantum information research, he can get rid of this problem. This will allow him to accurately obtain information through the projection of specific modal shapes.

Taking inspiration from work done with spatial optics, the group applied this thinking to measurement in time. Rather than being interested in how far apart two objects are, they were interested in measuring when two events occur relative to each other.

This is where the waveguide devices proved paramount.

The device is capable of decomposing pulses by their shape, rather than their time of arrival. Instead of asking when the pulse arrives, the device asks the pulse which specific superposition of times it could have arrived at. By decomposing the pulse into these shapes, properties such as the time difference and relative intensities of the pulses can be estimated efficiently.

In their experimental demonstration, the research group focused on how precisely they were able to estimate these parameters per photon measured. They found that their technique was a significant improvement over the existing best possible standard measurement.

Donohue hopes that these tools can be used and applied to quantum information, such as to measure pulse-shape entanglement between photons and study quantum communication.

"While these tools are very useful in classical optics, studying them with an eye on quantum information opens many new doors."

BRIGHT-LIGHT DETECTOR CONTROL EMULATES THE LOCAL BOUNDS OF BELL-TYPE INEQUALITIES

Published in Scientific Reports, August 06, 2020

<https://www.nature.com/articles/s41598-020-70045-7>

Nigar Sultana has her eyes set on outer space. Now completed her PhD in Electrical and Computer Engineering and Quantum Information at the University of Waterloo, Sultana is working with Thomas Jennewein on quantum communications satellites. This research mission is an important step toward a secure global communications satellite network.

Sultana began her university education in her home country of Bangladesh, where she completed an engineering degree. She earned her Master's and was a lecturer. It wasn't until she moved to the University of Waterloo in 2013 that she found a passion she enjoyed as much as teaching. She came to IQC as a research assistant to Thomas



Jennewein, a professor at IQC and in Waterloo's Department of Physics and Astronomy.

Sultana was able to put her engineering degrees to work while diving into the fields of quantum photonics. She worked her way through her PhD while designing advanced single-photon detecting systems for a collaborative satellite project with the University of Illinois at Urbana-Champaign: the Cooling, Pointing and Annealing Satellite (CAPSat).

"I want to do real experiments and see the outcome," said Sultana.

Sultana is excited to be participating in designing systems that will be launched into space. Her six-year quantum journey has resulted in her designing and building a quantum detector incorporating a laser annealing healing system for the CAPSat. The detectors going to space in the satellite for data testing must be able to heal themselves of the damage caused by being shot into space and the harmful radiation experienced once there.

Sultana notes that she had no working knowledge about satellites when she started her work at IQC. She had to learn everything about how to build a satellite payload and then make sure it could survive the rigours of space. "Everything matters, even the small things like glue," she said.

While she's focused on shrinking down her technologies — everything needs to fit in a satellite less than a thousand cubic centimetres — Sultana knows the impact of her work will be huge. Quantum Key Distribution (QKD) is a new communication system that secures information using the laws of nature and is robust against advances in computer technology, even quantum computers. By experimenting with quantum-capable satellites, researchers are working to one day establish a global communications network for a quantum-secured Internet.

"When Canada launches its first quantum satellite, I will be able to say I'm part of this," she said. "I worked on this."

DIRECT DISCRIMINATION OF STRUCTURED LIGHT BY HUMANS


Published in Proceedings of the National Academy of Sciences of the United States of America on June 30, 2020

<https://www.pnas.org/content/117/26/14682>

An experiment that began by testing the properties of quantum entanglement has led to the discovery of a new diagnostic tool that could help optometrists detect macular degeneration much earlier than was previously possible.

IQC researchers set out to test the human eye's ability to perceive one of the properties of quantum entanglement, but quickly realized that the tool they created to test their theory had an immediate practical use.

The IQC researchers then teamed up with researchers from the School of Optometry and Vision Science to use their work to design a unique form of light that is visible to people with healthy eyes, but not to people whose eyesight is degenerating.



“This started as an experiment to see how people can directly perceive a quintessential property of quantum entanglement,” said Dusan Sarenac, lead IQC researcher on the project. “But the collaboration quickly showed that these quantum applications can help humans right now.”

A person with healthy eyes can detect polarized light in the form of a blurry spot in their field of vision—a phenomenon known as Haidinger's brush. But those with unhealthy eyes—macular degeneration—can't see it at all.

People with an increased risk of developing macular degeneration would have a harder time seeing and tracking the polarized light profiles, the researchers reasoned. Intrigued by the hypothesis, the team prepared a unique form of light that would have particular polarization capabilities not commonly found in nature.

Using this quantum technology, the vision science team, led by Andrew Silva, ran an experiment with human participants. While a camera would only see a spot when looking at the light, the majority of participants were able to discriminate and respond to the profiles that are filtered by the healthy macula in the human eye.

Based on these findings, the team is currently developing a structured light microscope that will allow optometrists to image and track physiology of the eyes and in particular macular degeneration in patients. It is important, though tricky, to detect macular degeneration early in order to achieve the best treatment outcomes. Researchers aim to explore if this test will enable the disease to be caught earlier than current tests.

Sarenac and Silva are working with groups from IQC's Transformative Quantum Technologies (TQT) led by chemistry professor David Cory and physics and astronomy professor Dmitry Pushin, and with a group led by Ben Thompson, a professor at the School of Optometry and Vision Science.

SPIN-PRESERVING CHIRAL PHOTONIC CRYSTAL MIRROR


Published in *Light : Science & Applications* on February 20, 2020

<https://www.nature.com/articles/s41377-020-0256-5>

Researchers at the IQC have developed a new kind of mirror that could be used to protect against counterfeit banknotes.

Photons—quantum particles of light—can be left or right-handed, like humans. In some applications, researchers need to be able to sort left from right-handed photons, for example to study the arrangement of molecules in a drug.

In a recent study led by Behrooz Semnani, a second-year postdoctoral fellow at IQC and the University of Waterloo's electrical and computer engineering department, researchers created a 2D structure that, just like a mirror, reflects photons with one handedness but, unlike an ordinary mirror, lets photons with the other handedness through. The structure is a photonic crystal mirror: a thin membrane with a repeating chiral pattern of holes and looks like a very fine strainer. The term chiral means a pattern possessing handedness, and not matching its mirror image, like the letters S or Z.



The development of this new mirror will open up photon sorting in a wide range of industries, including the detection of counterfeit currency. Because the structure is less than a micrometer thick, it could be printed on government documents—such as banknotes—as a hidden security feature against counterfeiting.

“The structure is invisible to the naked eye,” Semnani said. “Its unique properties would allow the structure to be detected only upon inspection with light of the correct wavelength and polarization handedness. The structure can be mass produced, which is important for practical applications like detecting counterfeit currency.”

The research proves that photon sorting by left or right handedness can be done with thin 2D structures. This is counter to the previous belief that thick and complicated 3D structures were needed.

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

EXTRA STORAGE CAPACITY IN TRANSITION METAL OXIDE LITHIUM-ION BATTERIES REVEALED BY IN SITU MAGNETOMETRY

Published in Nature Materials on August 17, 2020

<https://www.nature.com/articles/s41563-020-0756-y>

+ Combined with

OPERANDO MAGNETOMETRY PROBING THE CHARGE STORAGE MECHANISM OF CoO LITHIUM-ION BATTERIES

Published in Advanced Materials on February 12, 2021

<https://onlinelibrary.wiley.com/doi/10.1002/adma.202006629>


A puzzle has baffled the battery industry for decades: certain materials used in the lithium-ion batteries that power our laptops, phones and cars store much more energy than theoretically expected.

Thanks to a research collaboration spanning three countries, this puzzle has been solved and researchers see opportunities to develop new technologies from batteries to quantum devices.

Researchers IQC, the Massachusetts Institute of Technology and the University of Texas at Austin, as well as Qingdao University and Shandong University in China, harnessed a technique normally used in physics to investigate batteries and discover their inner workings.

“The challenge is probing what’s going on inside of a battery non-destructively while it is operating,” said Guo-Xing Miao, associate professor at IQC and in the University of Waterloo Department of Electrical and Computer Engineering.

When you charge a battery by plugging it in or discharge a battery by using it, you may also change the magnetism within the battery. The researchers took advantage of this fact and used an in situ magnetometry technique to probe the internal magnetism of a battery in real time.



In a work published in Nature Materials in August 2020, they found that the extra capacity of transition-metal oxides often used as electrodes in lithium-ion batteries mostly resides in nanoparticles that physically collect around the surface of these materials after regular use of the battery. These clouds of nanoparticles hold the extra charge that has puzzled researchers for decades when only chemical reactions had been taken into consideration.

The researchers followed up this work by extending their results from iron oxide to cobalt oxide, another material with an unexpectedly high electrical storage capacity.

Published in Advanced Materials February 2021, the new work demonstrated that a polymer forms on the surface of cobalt oxide during normal use of the battery. The researchers used the magnetometry technique to show that this polymer, with the assistance of cobalt's catalytic properties, contributes to the extra storage capacity of cobalt oxide electrodes, in addition to the same nanoparticles that benefit iron oxide.

“Most commercial batteries will have a mixture at different transition-metal elements to balance their capacity, stability and cost,” said Miao. “With applied magnetic fields, batteries using these different elements can show magnetic signatures during the reactions as a non-destructive probing method.”

Now that researchers can probe the magnetic changes taking place in many different electrode materials, new avenues of understanding and developing battery technology can be explored.

Miao is also interested to see how this magnetometry technique can impact the next generation of quantum devices. “We borrowed this technique from spintronics where it functions the same, but with different applications,” said Miao.

Qiang Li, the lead author of the paper and an alumnus of Miao's group, now pursues his own research into spintronics as a professor at Qingdao University and an IQC Affiliate. “I became very interested in magnetism during my time at IQC,” said Li. “The magnetic manipulation with lithium ions is so powerful that it also opens a new route for controlling spintronic devices.”

Spintronics is the study of electron spin in solid state devices. By using the same magnetometry technique that allows them to probe batteries, researchers can read and write magnetic information at the level of the electron in spintronic devices, with ions as the new control knobs.

“In the same way that we can use an electric field to drive ion motion to change the magnetism in a battery, we can change the magnetism in a spintronic device to read or write information, or even to process information using logic gates,” said Miao.

Whether it is probing materials to find an advantage in the batteries that surround us or building the powerful quantum devices of the future, these new developments prove that sometimes the right piece to solve a puzzle is already out there. It just needs to be placed in the right spot.



SURFACE CODES: TOWARDS PRACTICAL LARGE-SCALE QUANTUM COMPUTATION [Foundational Research Contribution]

Published in Physical Review A 50th Anniversary Milestones in 2020

Originally published in Physical Review A on September 18, 2012

<https://journals.aps.org/pr/50th>

A research paper published in 2012 by Matteo Mariantoni, faculty member at IQC and in the University of Waterloo Department of Physics and Astronomy, appeared on the Physical Review A 50th Anniversary Milestones list.

The prestigious journal is celebrating its fiftieth anniversary with a list of papers that have made important contributions to the various areas of physics under its purview.

The article, Surface codes: Towards practical large-scale quantum computation, explained a new, more accessible approach to quantum error correction to the quantum information community and provided an early estimate of the infrastructure requirements for a practical quantum computer based on this approach.

The article went on to be cited more than a thousand times.

“When we wrote the article, I never expected it to be so impactful,” said Mariantoni. “It became a reference guide on quantum error correction and the difficulty of building a practical quantum computer for the quantum information community.”

The paper was also the beginning of the spread of quantum computing research from the lab to industry. “It served as a catalyst for many companies like Google and IBM to invest in quantum computing in a big way because there was this new positive thing to work on,” said Mariantoni.

Ironically, this paper that has impacted so many researchers began as an internal report. The Martinis-Cleland research group, where Mariantoni was a postdoc, was trying to understand what appeared to be a very promising paper on quantum error correction published by mathematicians Raussendorf and Harrington in 2007. At the time, Raussendorf was working from the Perimeter Institute in Waterloo, Ontario.

The team spent about nine months interpreting the article and translating its complicated mathematical language into something practical for experimental physicists. When they began to present their work at various events and saw the enthusiasm of their audiences, they knew they had something worth submitting for publication.

The rest is history.

While Mariantoni was at the University of California, Santa Barbara at the time of the publication, the work has influenced his research path ever since. “This article helped me realize what I should focus on for the past decade,” said Mariantoni.

The paper’s two key insights provided a bittersweet revelation for researchers looking to build the first practical quantum computer.

On the one hand, they now had a more accessible approach to quantum error correction that would allow them to begin working right away with hardware they already had. On the other hand, they now saw this approach would need an unfathomable number of

qubits—at least half a billion—to result in a practical error-corrected quantum computer.

For Mariantoni, this dual revelation suggested a research path; maybe the hardware itself can be improved enough to reduce the number and intractability of quantum errors so that quantum error correction and useful computation will be possible with a more practical number of qubits.

Now, Mariantoni and his team are working on a completely new approach to “outsmart” errors using phononic band-gap engineering.

“We are trying to combine many techniques which we know about superconducting devices to make them better, not even to remove these errors, but to make them better errors,” said Mariantoni.

Quantum errors still stand as a looming obstacle to practical quantum computing, but this seminal work on the surface code approach to quantum error correction shows what was possible and what is currently beyond reach, serving as a guidepost for thousands of researchers in the decade since.

Recruitment – Faculty

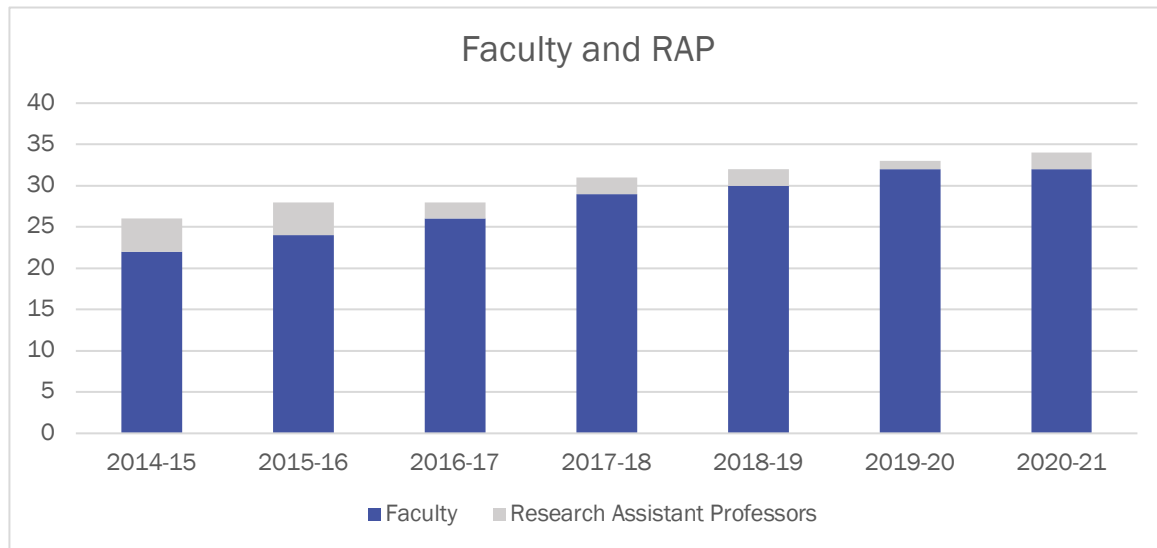
Alongside research and training, each year IQC prioritizes recruitment activities to continue to attract world-class theoretical and experimental researchers across of range of disciplines. Currently home to 32 faculty members who work in teams to pursue challenging problems in scaling complex quantum systems, this fiscal year IQC welcomed one new research assistant professor to its research community.



After completing undergraduate degrees in Mathematics and Computer Science at Sharif University of Technology in Tehran, Iran (2009) Dr. Pooya Ronagh received his M.S. and Ph.D. in Mathematics from the University of British Columbia in 2011 and 2016, respectively. Ronagh joined IQC in 2017 as a postdoctoral fellow, supervised by Dr. Raymond Laflame and Dr. Roger Melko before becoming a Research Assistant Professor at IQC and in the Department of Physics and Astronomy at the University of Waterloo.

Ronagh’s research interests involve algorithmic aspects of quantum computation. He explores novel applications of quantum computation by designing and analysing quantum algorithms for solving computational challenges wherein the classical state of the art is costly machine learning and high-performance computing. The symbiotic relationship between classical and quantum computing is not only important in unlocking applications of quantum computers but also crucial in building them. Dr. Ronagh is therefore also interested in using optimization and control theory to improve the hybrid quantum-classical schemes used for quantum control, quantum error correction, and fault-tolerant quantum computation.

The chart below illustrates the growth of IQC faculty and research associate professors over the last seven years.

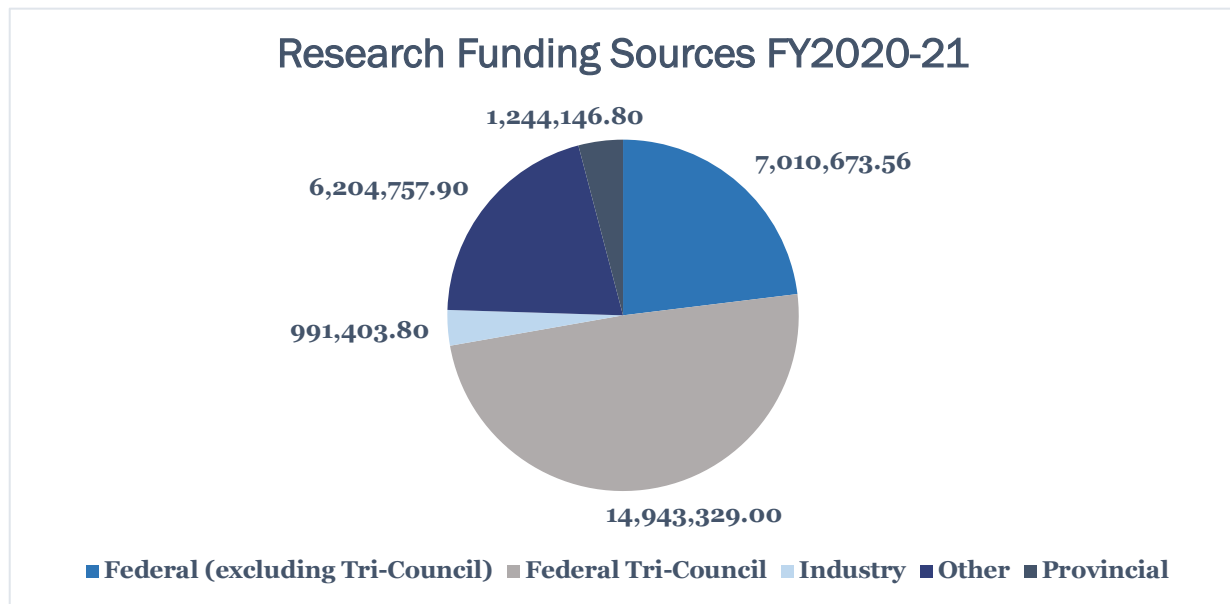


Recruitment – Research Associates

As international travel slowed due to Covid-19, IQC was able to continue world-class research projects by recruiting a number of research associates from the existing cohort of IQC postdoctoral fellows and recently completed doctoral students. Out of a total of fifteen Research Associates currently part of the IQC complement, seven were hired in 2020-2021. Three of the seven Research Associates are former IQC postdoctoral fellows, and one earned their PhD from IQC, which is a tribute 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. A full list of all 32 current faculty members, two research assistant professors, and fifteen research associates can be found in Appendix C beginning on page 67.

Awards & Research Chairs

IQC researchers have collectively been awarded \$30,394,311 in research funding during the period of April 1, 2020, to March 31, 2021. 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.



The calibre of quantum information research by IQC faculty members continues to make a global impact. The quality and ability of these members is evidenced not only by their research, but also by the many awards and acknowledgements they receive. In a globally competitive field, such awards reinforce IQC and Canada's excellent talent in quantum information. Below is a list of prominent awards faculty members received in 2020-2021:

Faculty Member	Award	Source
Michal Bajcsy	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
Jonathan Baugh	NSERC Discovery grant	NSERC
Raffi Budakian	NSERC Discovery grant	NSERC
Kyung Soo Choi	IOF Fund	Canadian Foundation for Innovation (CFI)
	NSERC Discovery grant	NSERC



Faculty Member	Award	Source
Richard Cleve	NSERC Discovery grant	NSERC
David Cory	John R. Evans Leaders Fund (JELF)	CFI - John R Evans Leaders Fund
	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
	Research Agreement	University of Maryland - College Park
Joseph Emerson	NSERC Discovery grant	NSERC
David Gosset	Quantum Information Science Program	CIFAR
	IBM Q Scholars	IBM US
	NSERC Discovery Accelerator Supplement (RGPA) Grant	NSERC
	NSERC Discovery grant	NSERC
Kazi Rajibul Islam	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
Thomas Jennewein	Canada-UK Quantum Technologies	Honeywell International Inc
	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Alliance grant	NSERC
	NSERC Discovery grant	NSERC
Na Young Kim	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
Raymond Laflamme	NSERC Discovery grant	NSERC
Debbie Leung	NSERC Discovery grant	NSERC



Faculty Member	Award	Source
Adrian Lupascu	NSERC Discovery grant	NSERC
Norbert Lutkenhaus	NSERC Collaborative Research and Development	NSERC - CRD
	NSERC Discovery grant	NSERC
Matteo Mariantoni	NSERC Discovery Accelerator Supplement (RGPAS) Grant	NSERC
	NSERC Discovery grant	NSERC
Guo-Xing Miao	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
Michele Mosca	Canada-UK Quantum Technologies	Crypto4A Technologies
	NSERC Alliance grant	NSERC
	NSERC Discovery grant	NSERC
	Canada-UK Quantum Technologies	Qeynet Inc
	Canada-UK Quantum Technologies	Rhea Group
	NCE-KM - Smart Cybersecurity Network	University of Montreal
Christine Muschik	CIFAR Azrieli Global Scholar	CIFAR
	Quantum Simulations of Fundamental interactions with Artificial Intelligence	NFRF
	NSERC Discovery grant	NSERC
Ashwin Nayak	Power and limitations of Quantum Algorithms	Fujitsu Laboratories of America Inc
Vern Paulsen	NSERC Discovery grant	NSERC
Dmitry Pushin	Quantum technologies for imaging of the human eye	NFRF
	NSERC Discovery grant	NSERC



Faculty Member	Award	Source
Michael Reimer	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
Kevin Resch	NSERC Discovery grant	NSERC
Crystal Senko	NSERC Discovery grant	NSERC
William Slofstra	NSERC Discovery grant	NSERC
	Alfred P. Sloan Research Fellowship in Mathematics	Alfred P. Sloan Foundation
Adam Wei Tsen	Early Researcher Award, Ontario	Ontario Ministry of Research, Innovation, and Science
	NSERC Discovery grant	NSERC
	US Army Research Office	US Army Research Office, US Army
John Watrous	Quantum Information Processing Program	Canadian Institute for Advanced Research
	NSERC Discovery grant	NSERC
Christopher Wilson	John R. Evans Leaders Fund (JELF)	CFI - John R Evans Leaders Fund
	NSERC Discovery grant	NSERC
	Demonstration of target ranging using microwave quantum illumination	Qubic Inc
Jon Yard	NSERC Discovery grant	NSERC

NB: This list is not exhaustive.

IQC is also home to the following Research Chairs:

- Crystal Senko, Canada Research Chair (2020-2025)
- Raymond Laflamme, Mike and Ophelia Lazaridis Chair (2017-2027)
- David Cory, Canada Excellence Research Chair Laureate (2017)
- Debbie Leung, University Research Chair (2015-2022)
- Kevin Resch, Canada Research Chair (2013-2023)

- Raffi Budakian, University of Waterloo Endowed Chair in Nanotechnology (2014-ongoing)
- Michele Mosca, University Research Chair (2012-2022)
- Raymond Laflamme, Canada Research Chair (2002-2022)

Infrastructure—Mike & Ophelia Lazaridis Quantum-Nano Centre

As of March 2021, there are 16 operational research labs in the Lazaridis Centre, with an additional research lab currently being finished for Alan Jamison.

One of the more recent experimentalists to join IQC, Dr. Jamison is currently operating an existing lab while the necessary renovations to complete his custom lab are finished. Selected labs are listed below :

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

In addition to the building of new labs IQC continues to improve the quality of our existing infrastructure. For example, the Quantum Outreach 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.

For the IQC community and the campus community at large our dedicated two-storey seminar space (QNC 0101) is currently being refurbished to update the lighting, improve the audio-visual capabilities and refresh the physical space. This seminar space will be able to host mid-size functions for all audiences when the work is complete.

Lastly, to support the commercial/industrial community IQC contributed significant funding towards the acquisition of a new S/TEM system to replace an aging unit that is 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 will be delivered in Q1 2022. This is a major acquisition and will rank amongst the versatile systems at IQC. The addition of this tool to our existing ensemble of great analytical capabilities will undoubtedly benefit our existing and future lab members.



Infrastructure–Quantum-Nano Fabrication and Characterization Facility

The Quantum-Nano Fabrication and Characterization Facility (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 15,326 hours of independent lab equipment use logged by registered lab users. The drop in usage is due to the COVID-19 pandemic, notably:

- Lab operations were forced to shut down on March 18, 2020 and the facility remained completely closed until July 13, 2020 due to COVID-19 restrictions.
- Since July 2020, the facility's hours of operation have been reduced by 64%. Specifically, the QNFCF is only open 60 hours per week versus the facility's previous 24/7 hours of operation (168 hours per week).
- Restrictions on equipment use due to physical distancing constraints may have also impacted annual equipment use trends.

However, recent trends show increasing and widespread use of QNFCF. The examples include:

- In spite of the reduced hours of operation, month-over-month equipment use trends have been increasing steadily since January 2021.
- 2769 hours of equipment use were logged over the course of the month of March 2021; this compares favourably with the 2697 hours of use logged over the course of February 2020 (pre-pandemic) which is significant given the facility's continued reduced hours of operation (only open 60 hours per week).
- Hours of operation are likely to be expanded later in the 2021/22 fiscal year as the COVID-19 situation improves.
- 700+ hours of hands-on equipment user training; in addition, many hundreds of hours of ongoing process support and guidance engineering staff provide to QNFCF membership.
- 2400+ 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.

The facility was actively used by 154 people over the course of the year. Each of these people is affiliated with one of 62 different research groups from across campus and Canada which made use of the QNFCF for their respective research programs this past year.

It is also noteworthy that during the pandemic the QNFCF provides the critical infrastructure in multiple COVID-19 research efforts. Direct projects include the below.

- Researchers looking at virus-like particles and/or viral proteins (e.g., SARS-CoV-2 spike) in solution. The goals are to understand better the entry mechanism of the SARS-CoV-2 with the host cell and the interaction between the external protein of SARS-CoV-2 (spike) and drugs or antibodies.
- Developing phase-contrast X-ray detectors and technology which are critical for COVID research, specifically the efficacy of reused masks.
- Imaging antiviral metal and metal oxide coatings on polypropylene fabrics used in N95 masks.

Taking advantage of the high-Q engineered terahertz (THz) resonator, researchers are aiming to form a reliable platform for real-time, cost-effective, and in vivo biomolecular sensing and identification. The THz biosensors will potentially play a critical role in efforts to combat the ongoing COVID pandemic.

The IQC and CFREF-TQT (Transformative Quantum Technologies) programs support the QNFCF operations and in 2020-2021 contributed over \$760k to cover staff salaries, equipment acquisitions and equipment service contracts.

Infrastructure – Research Advancement Centres (RAC)

As of March 31, 2020, there are 7 operational research labs in RAC (I and II), which include:

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

In RAC I, the design and assembly of the Quantum Explorations Space is complete. This space will be used to support students in the new MSc. Physics (Quantum Technology) degree offered at Waterloo in partnership with IQC and TQT. This lab is used to give students and visitors access to real, research-grade quantum systems for laboratory experiments and knowledge building. Highschool and undergraduate students in programs such as Quantum Cryptography School for Young Students (QCSYS) and Undergraduate School on Experimental Quantum Information Processing (USEQIP) also get detailed hands-on experience with real systems. In future, it will allow large numbers of industry experts and visitors to see quantum devices in action.

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 2020-2021, IQC faculty members collectively reported 113 active collaborations with 103 unique organizations that span the globe. The following list of organizations includes examples of such organizations and includes universities, research institutes, private corporations, and government. A full list of collaborations can be found in Appendix D on page 68.

- Anyon Systems
- Honeywell (formerly called ComDev)
- National Research Council
- Canadian Space Agency
- Xiphos Systems
- National Institute of Optics, Canada
- University of Southern California
- Swiss Federal institute of Technology
- InfoSec Global
- University of Ottawa
- DARPA
- Chinese Academy of Sciences
- Excelitas
- Perimeter Institute of Theoretical Physics
- University of Maryland
- Mitacs
- Sandia National Labs
- NIST Boulder Laboratories
- Cornell University
- University of Vienna
- Université de Montréal
- ID Quantique
- Centre for Quantum Technologies
- Technion, Israel Institute of Technology
- University of Texas at Austin
- University of Calgary

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:

- Meetings between IQC and the Office of the Chief Scientist at National Resources Canada (NRCan) led to discussions about how IQC's current and future research may have applications in the natural resources sector. As the natural resources sector is well-positioned to be an early adopter of quantum technologies, these discussions identified potential collaboration areas. To develop these potential partnerships further, IQC and NRCan scheduled a series of researcher-to-researcher meetings and roundtable discussions to take place virtually in May 2021.

- IQC participated in the NSF Workshop on Quantum Engineering Education, held on February 25-26, 2021, focusing on methods of introducing undergraduate quantum education to universities in the United States. IQC and the University of Waterloo were recognized as an international leader in this regard, with former IQC staff member Martin Laforest invited to present a talk titled "Building a Quantum Workforce Starts Early" and current IQC Senior Manager, Scientific Outreach John Donohue invited to contribute to the roadmap article on quantum engineering education, to be published in Physical Review X Quantum.
- IQC focused on building relationships with startup incubators and Canadian venture capital firms to highlight learning and training opportunities for IQC researchers interested in learning how to commercialize their research. More detailed information on individual meetings and events throughout the 2020-2021 year can be found on page 55 as part of Objective E.

Objective B

Create new opportunities for students to learn and to apply new knowledge to the benefit of Canada, spurring innovation, and investment in R&D activities through highly qualified personnel development.

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
- Launching a new program - M.Sc. Physics (Quantum Technology) - to provide students with hands-on learning on quantum platforms and produce students capable of driving growth in new quantum industries.
- Fielding at least 200 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 logistical restrictions are reduced
- Hosting up to 10 virtual workshops and seminars
- Jointly sponsoring up to 10 workshops and conferences with national and international partner organizations

Attracting Talent – Postdoctoral Fellows

Postdoctoral fellowship positions provide young scientists opportunities for additional mentoring, publications and for research and teaching experience. In 2020-21, IQC recruited 17 new postdoctoral fellows – four 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 under enormous travel restrictions.

In total, over the last fiscal year, IQC employed 85 Postdoctoral Fellows, of whom, 15 were women. As outlined in the table below, newly recruited fellows came from prominent institutions in Canada and around the world.

A full list of current postdoctoral fellows can be found in Appendix E on page 72.


Canada	International	United States
Université de Sherbrooke	University of Warwick United Kingdom	University of Louisiana
University of Toronto	Centre for Secure Information Technologies, Queen's University Belfast, Northern Ireland	University of California, Los Angeles
University of Waterloo	Institut National de la Recherche Scientifique (INRS) Dual PhD with Université de Bordeaux, France	

Since 2015, 14 IQC PhD alum have been awarded postdoctoral fellowships. These alum represent a group of early researchers dedicated to advancing their work in quantum information at IQC. In addition to attracting highly qualified students, IQC postdoctoral fellowships are a proven method for IQC to recruit future IQC faculty members. Prior to joining IQC as a Research Assistant Professor, Pooya Ronagh held a postdoctoral fellowship at IQC.

Attracting Talent – Graduate Students

IQC welcomed 48 new graduate students this past year from 434 applications, bringing the total current number of Master's and PhD students to 197 (84 and 113, respectively). As with Postdoctoral fellows, in 2020-21 IQC saw a slight dip in total graduate students. This dip is a function of increased travel restrictions, uncertain arrival requirements and reduced access to labs and classrooms. As the pandemic resolves itself over the next 4 months, IQC expects these numbers to recover and continue on an upward trend.

Canada	International	United States
McGill University	Moscow State University	Dartmouth College
University of Toronto	Beijng Jiaotong University/UW (2+2)	University of California Berkeley
University of Waterloo	Indian Institute of Technology Kharagpur	Massachusetts Institute of Technology
Memorial University of Newfoundland	University of Cambridge	Harvard University
University of British Columbia	Monash University	Yale University



A full list of current graduate students currently studying at IQC can be found in Appendix F on page 73.

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 not only provide students with the funding needed to devote themselves to their studies, but also demonstrate their research excellence. In the last year, 166 IQC students were collectively granted 452 separate awards (with an additional 18 Covid-19 Scholarship Extensions also awarded to IQC students).

Of the 166 IQC students that earned awards and scholarships, 31 were female and 10 additional students did not report gender. These students earned 127 (28%) of the 452 awards and demonstrate that IQC is committed to equity, diversity and inclusion. To promote these goals, IQC endowed and awarded the *Raymond Laflamme and Janice Gregson Graduate Scholarship for Women in Quantum Information Science* in 2020-2021. To be accountable for progress on these goals, IQC announced its membership in the Innovation, Science and Economic Development Canada 50-30 challenge in March 2021.

The list below highlights some of these top awards, scholarships and fellowships our Master's and PhD students received:

- 16 Mike & Ophelia Lazaridis Fellowships
- 1 IQC Entrance Award
- 47 International Doctoral Student Awards
- 30 International Master's Awards of Excellence
- 1 IQC Achievement Award
- 2 IQC David Johnston Award for Scientific Outreach
- 6 NSERC Alexander Graham Bell Canada Graduate Scholarships - Doctoral
- 8 NSERC Alexander Graham Bell Canada Graduate Scholarships - Masters
- 6 NSERC Postgraduate Scholarships - Doctoral
- 2 NSERC Vanier Canada Graduate Scholarships
- 5 Ontario Graduate Scholarships
- 33 President's Graduate Scholarships
- 1 Raymond Laflamme and Janice Gregson Graduate Scholarship for Women in Quantum Information Science
- 1 Ontario Trillium Scholarship

- 3 QEII-Graduate Scholarships in Science and Technology

Attracting Talent – Undergraduate Students

IQC offers many opportunities to expose undergraduate students to research. Students can apply primarily in tandem with applications to the annual Undergraduate School for Experimental Quantum Processing (USEQIP) for a chance to stay for a research term following the program, or they can apply for a research position outright. Uncertainty surrounding travel, residency and building access early in the Covid-19 pandemic resulted in the cancellation of USEQIP for May 2020 but the Undergraduate Research program was continued remotely. Undergraduate research assistant positions provide students with the unique opportunity to work alongside a faculty member or research assistant professor and interact with our interdisciplinary research community.

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 existence (2009), a total of 22 past USEQIP participants have returned to IQC to pursue graduate studies. USEQIP participants often note that advanced degrees seem more accessible after participation in the program and are attracted to IQC in particular:

“USEQUIP is a rare program that gives a combination of lectures and labs, delving deeply into quantum information in a way we can't otherwise access in our undergrad ... it feels like everyone has become substantially more ambitious with respect to their academic goals. Things that felt out of reach in the past don't feel so distant anymore.”

“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!”

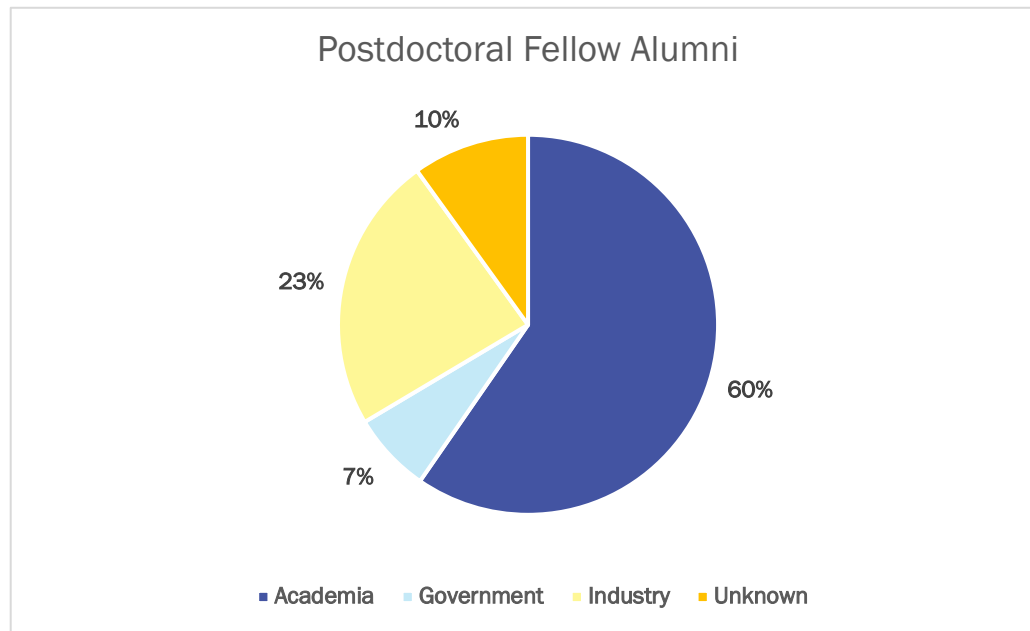
“I very much enjoyed my time at IQC and I am seriously considering [it] as a place to do my masters.”

IQC Alum: Building the Quantum Workforce

IQC student and postdoctoral alum leave to become global citizens who impact 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.

Postdoctoral Fellows Alum Overview

After leaving academia, postdoctoral fellow alum are regarded as role models, visionaries, and leaders of the quantum industry, by their peers. Our alum leave campus and become global citizens who impact academic, industry and government sectors. Below is a representation of where IQC postdocs have gone as of March 31, 2021:



PostDoc Alum Profiles

Dave Touchette

After completing a postdoctoral fellowship at IQC in 2019, Touchette returned to his native Quebec when he accepted a position as an assistant professor at Université de Sherbrooke. He became the first professor in the department of Computer Science at Sherbrooke to join the Institut Quantique, a natural evolution of the research he undertook at IQC.

At IQC, Touchette worked with a variety of faculty members including Ashwin Nayak, Debbie Leung and Norbert Lütkenhaus. His current research is focused on Complexity, Information Theory and Quantum Communication with an eye towards training not only future researchers, but also a quantum workforce that can quickly meet the needs of an evolving industry.

Jay Gambetta

Jay Gambetta completed his postdoctoral fellowship at IQC in 2011 with a research focus on quantum information processing with superconducting qubits. During his time at IQC, he gained a Junior Fellowship from the Canadian Institute for Advanced Research (CIFAR, 2009). Since leaving IQC, he continues to investigate quantum

information processing at the Thomas J. Watson Research Center in Yorktown Heights, New York where he is an IBM fellow and Vice President, Quantum Computing.

Gambetta's work with superconducting qubits, among other topics, is promising for the future of quantum computation and the development of a quantum computer. As a quantum law comparable to Moore's Law, the idea that Quantum Volume is doubling every year is known as Gambetta's law.

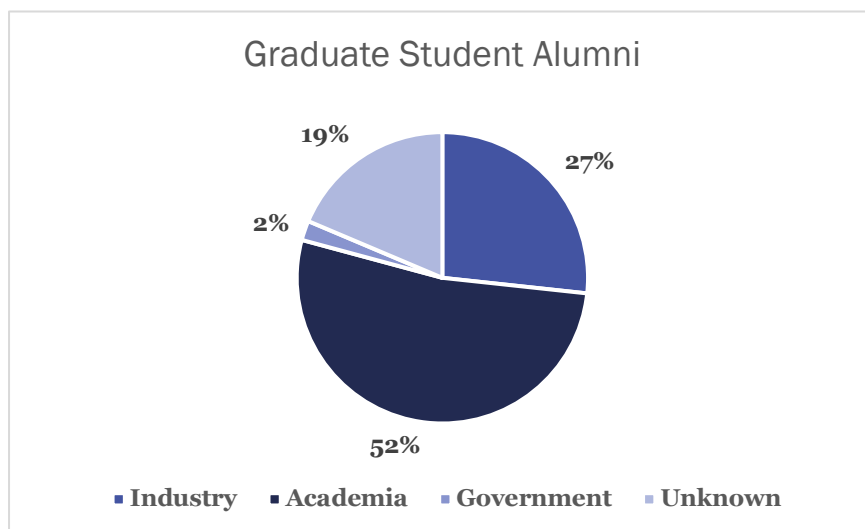
Razieh Annabestani

Razieh Annabestani earned her PhD with Professor David Cory at IQC in 2016. Her PhD research was mainly focused at the border of quantum information theory and nuclear magnetic resonance spectroscopy. She continued on at IQC as a postdoctoral fellow from 2016-17 and focused her research on nano-MRI imaging, which aims at the ultra-sensitive detection of electron and nuclear spins and could impact fields ranging from medicine to materials science.

Currently, Dr. Annabestani is a Quantum Strategy Advisor to the Government of Canada and is working to ensure that Canada and IQC build on their strong quantum programs and maintain our world-leading research programs.

Graduate Students Alum Overview

This year, IQC proudly reports granting degrees to 17 Master's students and 21 PhD students, bringing the total number of student alum to 307 cumulatively. These researchers are employed in a diverse range of positions – from academia to industry to government – both within Ontario and around the world. As of March 31, 2021, 34 IQC graduates are working in the Quantum Information (QI) field in Canada, of which 6 are women. An additional 18 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 Alum Profiles

Helen Percival (MSc Electrical and Computer Engineering—Quantum Information)

Now a Systems Engineer at SED Systems, a satellite communications and management company, Helen Percival applies the skills she gained working on large projects at IQC with supervisor Christopher Wilson. Her Master's research was focused on using experimental superconducting qubits for microwave control.

“During my time at IQC, I found my passion for engineering design,” Percival says. “It prepared me for working in an interdisciplinary field, tying different concepts together while keeping the big picture in mind.”

Mária Kieferová (PhD Physics—Quantum Information)

While studying theoretical physics at Comenius University in Bratislava, Slovakia, Mária Kieferová completed internships at IQC as a master's student with Michele Mosca and Nathan Wiebe, which eased her transition to the University of Waterloo as a PhD student in the Department of Physics and Astronomy and at IQC.


During her PhD, she focused on devising new algorithmic techniques that can be used for a variety of applications, for example in machine learning or chemistry. “I like that I can make an impact while learning about new applications of quantum computing,” said Kieferová.

Kieferová felt her work was validated when she received an IQC achievement award for her research excellence in 2019. “I'm very happy I studied at IQC,” she said. “Being a woman and from a small country, I have never felt like I belong to the scientific community. Being awarded for my research means that I am doing all right after all.”

After her PhD, Kieferová started as a postdoc at the University of Technology Sydney, Australia, where she continues to work on quantum algorithms, but also studies complexity theory and the possibility of connecting quantum computers through a quantum internet. She also keeps in touch with industry by working part-time at Zapata Computing developing software for near-term quantum computers.

Corey Rae McRae (PhD Physics—Quantum Information)

While completing her PhD studies at IQC, Corey Rae McRae's research was focused on the 3D packaging and integration of superconducting quantum circuits, and materials in superconducting quantum circuits. Her experimental work in the Digital Quantum Matter lab with researcher Matteo Mariantoni included the simulation, design and development of fabrication processes for superconducting microwave resonators and the design of a superconducting capping and bonding method that is compatible with superconducting quantum circuits.



Currently working as a postdoctoral researcher at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, McRae is working with state-of-the-art fabrication techniques to build robust qubits as she continues research towards the realization of an extensible universal quantum computer. She is also director of the Boulder Cryogenic Quantum Testbed at JILA Colorado.

McRae credits IQC for her career preparation in the quantum computing field. “When I started at IQC, I knew very little about quantum computing and quantum information,” she said. “IQC provided me with a well-rounded view of these areas and how they fit together, an integral step for a career in quantum information science.”

New Quantum Technology Program: Master of Science in Physics

IQC is the product of an early investment by a business visionary in a field that was only emerging in 2002. After 20 years of world class research across 3 disciplines the field of quantum information science is beginning to be incorporated into the business plans of large multi-national organizations and is spinning off start-ups at an impressive rate.

IQC is taking the next step to support an emerging industry that it is largely responsible for creating and introducing a new master's program that is intended to supply the highly skilled workforce that this new industry will need. Launching September 2021, this program will prepare alum to join quantum industry, participate in quantum startups, lead the analysis and support of quantum adoption as well as to enter PhD programs. This 12-month, course-based master's degree will provide in-depth knowledge of the science and technology of quantum systems with hands-on learning on quantum platforms including superconducting electronics, atomic, molecular and optical systems and solid state devices. IQC is eager to continue its pioneering support of quantum information and is looking forward to producing highly qualified personnel to drive this emerging industry forward.

Expanding Connections

IQC's graduate student recruitment efforts have continued virtually, with IQC staff reaching out to students at events like the Canadian Undergraduate Physics Conference (CUPC), the Canadian Conference for Undergraduate Women in Physics (CCUWiP), and the Atlantic Undergraduate Physics and Astronomy Conference (AUPAC), and graduate fairs run by McGill University and the University of Waterloo.

IQC researchers have continued to give many talks virtually throughout the pandemic across Canada and the world. Some examples include:

- Six IQC faculty members participated in Quantum Days Conference in January 2021, including Michele Mosca, Norbert Lutkenhaus, Thomas Jennewein, Richard Cleve, David Gosset and Christopher Wilson contributing on each day of the 3-day conference.

- John Donohue, IQC Senior Scientific Outreach Manager, moderated a panel discussion focusing on challenges need to be met over the next five years of quantum research and development.

Part of recruiting and retaining talent relies on building a strong and stimulating research environment. As a leading institute, IQC is proud to be part of many national and international conferences, workshops and seminars held by and for researchers. This is a key priority as conferences and talks foster collaboration and promote the exchange of ideas.

While the global pandemic had a significant impact on this IQC portfolio item, it is worth noting that switching to online presentations provided an opportunity to measure widespread interest in quantum topics and the results were encouraging. While some engagements had to be cancelled other engagements were adapted to a virtual format and achieved significant increases in attendance where geographic or financial barriers to attendance were removed.

Workshops

Schrödinger's Class, November 30-December 6

At the end of November and start of December, IQC hosted its sixth annual high school teacher workshop, Schrödinger's Class. Here, teachers attended virtual lectures on quantum fundamentals and investigated ways to integrate quantum technology into their current teaching curriculum. This workshop also provided teachers an opportunity to learn about cutting-edge advances in the field.

In FY2020-2021 Schrödinger's Class was delivered online and recorded a significant increase in participation. In FY2019-20 IQC was able to host 39 participants in-person, in FY2020-21 IQC hosted 130 people and found 112 teachers were highly engaged² with the curriculum, this represents an almost 300% increase in attendance – something that IQC could not accommodate in-person at this time. Geographically remote instructors, including at least one instructor from Arizona, were able to participate in this workshop.

Major Conferences

IQC remains committed to hosting conferences in Waterloo and are actively planning for conferences when they can be hosted safely for a wide variety of audiences. How soon IQC can host a conference depends on the resolution of the current pandemic. Historically, IQC has hosted major conferences for high school teachers, young postdoctoral fellows and researchers from across the spectrum of quantum information science research.

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 34

² Attended at least 2/3 of the sessions and for each session attended more than 90% of the instructor minutes.

seminars, 17 of which were delivered by and for students and 10 colloquia. The student seminar series introduced in FY2019-2020 continues to serve as a way to interconnect IQC members, allowing students to share results of their ongoing research, be exposed to research outside of their immediate research area, and to serve as a platform to develop presentation skills. The decrease in number of seminars is due to COVID-related cancellations in April and lingering uncertainty regarding campus access before transitioning these events to an online format through summer 2020.

These seminars (excluding student seminars) and colloquia were uploaded to the IQC YouTube channel. On YouTube, these seminars and colloquia garnered over 5,000 views and over 500 hours of viewing time, significantly expanding the viewership beyond the live attendees. The demonstrated interest in these topics has inspired IQC to continue uploading these sessions in the future.

Sponsored Conferences & Workshops

Each year, IQC commits to supporting external conferences and workshops to encourage opportunity for collaboration among a global network of researchers. Travel restrictions and the Covid-19 pandemic limited both the number of conferences and the need for funding in this fiscal year. In the future IQC remains committed to supporting external quantum events and, even this year, IQC sponsored 4 external partner events which are listed in the chart below:

Date	Conference	Location
June	Canadian Association of Physicists (CAP) Congress	Virtual
October	International Space Apps Challenge	Virtual
January	Canadian Conference for Undergraduate Women in Physics (CCUWiP)	Virtual
February	Atlantic Undergraduate Physics and Astronomy Conference	Virtual



Objective C

Brand Canada as the destination of choice for conducting research in quantum technologies and attract the best in the world to Canada, creating partnerships with the international quantum information community and promoting a world-class excellence in quantum information science and technology.

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 (incl. 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 at least four 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

Canada is internationally recognized as a leader in quantum information and technology research. Each year IQC faculty members, postdoctoral fellows and graduate students represent Canada on the international stage highlighting the excellent talent and capacity the country has built. Many of those achievements are highlighted throughout this report and in the appendices.

Additional initiatives include those undertaken by the larger IQC community including the Canada-UK Quantum Technologies Competition where IQC faculty earned three out of eight projects. This competition is the result of an industry-led partnership between the two countries to develop quantum technologies. The winning IQC projects are:

Reference-Frame Independent Quantum Communication for Satellite-Based Networks (ReFQ) – IQC Academic Lead Thomas Jennewein, IQC co-applicant Norbert Lutkenhaus



This project brings together experts from Canada and UK to demonstrate the use of quantum technology for protecting commercial and national communications networks. This project will implement a new approach and protocol that improves the integration and alignment of a quantum transmitter on a satellite. The UK-CAN Quantum Key Distribution (QKD) technology developed in this project is targeted to fly onboard Canada's Quantum Encryption and Science Satellite (QEYSSat), thereby extending the scope of the mission and demonstrating links to ground stations on both sides of the Atlantic.

Making noisy quantum processors practical: from theory to applications –
IQC Academic Lead Raymond Laflamme

This project unites experts in industry and academia with extensive experience in quantum computing to develop robust implementations of quantum algorithms that can run successfully on today's error-prone quantum processors. It will speed up the demonstration of quantum advantage for industrially relevant problems such as the simulation of quantum systems.

Building a standardised quantum-safe networking architecture – IQC
Academic Lead Michele Mosca, IQC co-applicant Norbert Lutkenhaus

The team includes academic, industry and government partners working to bring together Quantum Key Distribution (QKD) and Post Quantum Cryptography (PQC) technologies and designs from both countries and combine them in order to develop a Canadian-UK secure network built on the security principles of quantum-safe technologies.

Be a catalyst for collaborations of quantum information scientists

IQC provides an atmosphere that encourages and celebrates collaborations at every level. Below are descriptions of collaborative projects that were either initiated or continued over the past year. Appendix D, on page 68 provides a full list of all collaborative efforts this year (note: this list does not include co-authored publications.)

CIFAR Quantum Information Science Program

Brings together physics, mathematicians, computer scientists and others to address the most fundamental questions in Quantum Information Science. There are 34 members total – three of which are IQC faculty members and two are IQC Affiliates. The Quantum Information Science program was founded in 2002 and renewed in 2007 and 2012.

NRC High-throughput and Secure Networks Challenge (HTSN)

IQC faculty member, Thomas Jennewein is collaborating with the National Research Council team tasked with creating technologies enabling the implementation of next-generation, and next-after-next generation high speed telecommunication networks.



NRC Quantum Sensors Challenge Program

NRC's Quantum Sensors Challenge Program is designed to position Canada in a global leadership position on emerging high precision quantum sensors. IQC faculty member Kevin Resch was recruited to sit on the Expert Panel Review Committee for this challenge. This request recognizes the prominent position of IQC faculty on quantum topics in Canada.

Promote collaborations through participation in national and international conferences

IQC is dedicated to finding opportunities to participate in national and international conferences. Collectively, 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 and/or attended. A complete list of conference participation is listed in Appendix G on page 76. Please note, these talks were all delivered virtually this year.

- Interfacing quantum dots with laser-cooled atomic ensembles, Optical and Quantum Sensing and Precision Metrology
- Network architecture for quantum computing in silicon, University of New South Wales Physics seminar
- Embezzlement of entanglement, Reading group in Dept. of Mathematics, UC Berkeley
- Common Criteria Protection Profile Activity at ETSI, ETSI ITU meeting on Standardization
- Fast simulation of planar Clifford circuits, Los Alamos National Lab Quantum Lunch Seminar
- Advancing satellite-based quantum communication channels, Qtech 2020
- Novel avenues for robust free-space quantum communications, Colloquium, Max-Planck-Institut für Quantenoptik
- Embezzlement and applications, Tutte Colloquium, University of Waterloo
- Quantum data compression, Stanford Compression Workshop 2021
- Implementation of a high-fidelity Walsh-Hadamard gate with superconducting qutrits, University of Calgary, Canada
- A measurement-based variational quantum eigensolver, University of Toronto
- Applications of the information-theoretic method in quantum computation, IQUIST seminar, Illinois Quantum Information Science and Technology Center, University of Illinois Urbana-Champaign
- Playing Games with Quantum Probabilities, Missouri University of Science and Technology
- Entanglement Breaking Maps and Zauner's Conjecture, Codex Seminar

- High efficiency single-photon detector based on semiconductor nanowires, Advanced Photon Counting Techniques XIV, SPIE Defense + Commercial Sensing
- Quantum simulation tools using trapped ions, APS Division of Nuclear Physics
- Tunneling Probe of Two-Dimensional Magnetism, Cal State Long Beach
- Quantum Simulation and Computation with Microwave Photons, Physics Colloquium, Purdue University
- 2020 Canada-Korea Conference on Science and Technology
- Bloch Exciton-Polaritons and Rydberg Excitons, University of Strathclyde

Organize conferences with multidisciplinary participants


When planning major conferences, IQC remains committed to promoting the multidisciplinary basis of quantum information science. Due to pandemic restrictions IQC was unable to organize larger-scale conferences in FY2020-21. Instead, we pivoted to smaller virtual meetings and round table discussions with domestic and international organizations. In FY2021-2022, we are exploring hybrid conference models and technology. We look forward to continuing our past successes with the Ontario Association of Physics Teachers and Quantum Innovators in Science, Engineering, Computer Science and Mathematics.

Long-term Academic & Scientific Visitors

IQC host leading academic visitors from organizations around the world. These colleagues and collaborators come for a number of reasons and stay for varied amounts time to conduct research, collaborate, share knowledge and present talks. In FY2020-21, IQC researchers virtually hosted 18 visitors from around the world. Visiting organizations included:

Domestic	International	United States
University of Alberta	University of Copenhagen	Massachusetts Institute of Technology
York University	Universidad Complutense, Madrid, Spain	University of Maryland
	India Institute of Technology, Bombay	University of California, Berkeley
	Tsinghua University	

Over the last year, IQC has built new and strengthened existing relationships with other Canadian universities and organizations in quantum research and technology. We leveraged technology to continue to offer our Visitor Program and bring leading



international researchers to the Institute. In FY2020-21, 89% of scientific visitors were from outside Canada (16/18).

A full list of academic and scientific visitors can be found in in Appendix H on page 86.

IQC online: Innovative New Virtual Tour

Hosting tailored tours for industry, academia and government has always been a key component of IQC advancement activities. Public health restrictions eliminated the possibility of in-person tours but IQC has developed an innovative virtual tour that will continue to be used for remote stakeholders even after current in-person restrictions are lifted.

The virtual tour was created in-house using specialized hardware and hosted on a virtual tour platform online. Similar to visiting the Mike and Ophelia Lazaridis Quantum-Nano Centre in person, the virtual tour is guided by IQC staff and highlights the Quantum Nanofabrication and Characterization Facility (QNFCF), the collaboration and mind spaces within IQC, and takes viewers into the lab showcasing the equipment and research spaces. The 3 labs it covers are the Engineered Quantum Systems Lab, the Quantum Photonics Lab, and the Quantum Information with Trapped Ions Lab. Enhanced multimedia features include additional photography and video to provide further context to the scale of the fundamental research happening at IQC.

With the 360-tour completed by the end of 2020, IQC conducted several virtual tours with participants from National Research Council, Natural Resources Canada and industry stakeholders. The virtual tours lead to collaboration meetings as partnership potential continues into FY2021-2022.



Objective D

Enhance and expand the Institute's public education and outreach activities to effectively promote science and quantum information science and demonstrate how the research from quantum information science can be applied for the purpose of sustaining and attracting world class talent.

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.

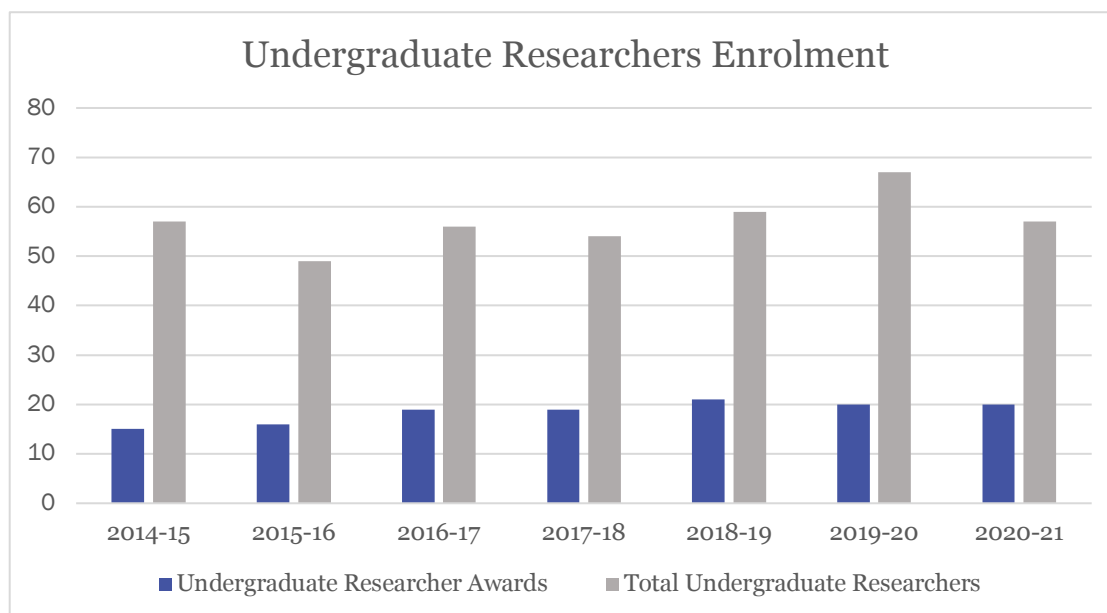
Planned Activities:

- Hosting USEQIP (undergraduate) and QCSYS (high school) summer schools
- Hosting the sixth 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

USEQIP

In FY2020-21 IQC had planned to host its 11th annual Undergraduate School for Experimental Quantum Information Processing (USEQIP) from May 25 to June 5. This program typically consists of lectures introducing quantum information theory and experimental approaches to quantum devices, followed by 30+ hours of hands-on exploration of Quantum Information Processing (QIP) using the experimental facilities at IQC.

Unfortunately, due to uncertainty early in the Covid-19 pandemic beginning in mid-March 2020 IQC did not have time to create a virtual version of USEQIP and it had to be cancelled entirely. However, the IQC Undergraduate Research Awards (URA) program was continued with minimal reduction and 20 of the 21 USEQIP/URA applicants were able to work with world class researchers at IQC remotely.



QCSYS

IQC hosted its 12th annual Quantum Cryptography School for Young Students (QCSYS) summer school from August 3 to 14. As QCSYS was redeveloped for virtual delivery, the final program included 19 lessons spread over 10 weekdays.

In August 2019 IQC was able to accept 44 students from 309 applicants. In August 2020 with a virtual format IQC was able to accommodate 110 highly engaged³ high school students from around the globe. As with IQC public lectures and Schrödinger's Class, QCSYS's jump in enrolment indicates an extraordinary interest in quantum topics in various audiences, such as young students and the general public, and IQC's reputation as a world-class institute for quantum information science research.

In a survey of the students following the summer school, 97.47% of respondents rated their overall experience at QCSYS as excellent (73.42%) or good (24.04%). 100% of respondents said that they would actively encourage people to apply (71.60%) or if asked, they would encourage people to apply (28.40%). 82.5% of respondents strongly agreed with the statement, "QCSYS exposed me to ideas not available in my high school classes."

"This was such a wonderful program and I am so glad that I was accepted and able to join QCSYS. This program has taught me so much and I feel much more prepared for my future now that I have learned lots

³ Attended more than 75% of all lectures – at 50% attendance 127 students attended.

about quantum computing. The past two weeks were the best weeks out of my whole summer.”

“I truly loved attending QCSYS online. It was a tremendously fun experience getting to meet other students from various places and similar [quantum mechanics] interests, as well as learning from lecturers and expert researchers in this field. It was an amazing experience, and I am so thankful that I was able to attend.”

Schrödinger’s Class

IQC hosted its sixth annual high school teacher workshop, Schrödinger’s Class, from November 30 – December 6.

In 2019, IQC received 112 applications to Schrödinger’s Class and could only accommodate 39 participants indicating growing interest in the program. To accommodate the interest IQC had already planned to have two separate streams of Schrödinger’s Class in 2020. Holding the class as two separate virtual streams was very successful; as noted above (pg. 40) IQC measured a marked increase in the number of engaged high school teachers which we were able to accommodate in a virtual format.

Stream 1 was the weeknight stream that occurred on 3 evenings from November 30 – December 4. Stream 2 was the weekend stream that occurred on December 5 and 6. Both streams included 3 90-minute sessions, which included lectures provided by John Donohue and multiple breakout discussions. The 3 session topics were: Quantum Superposition & Light Polarization, Wave-Particle Duality and Interference, and The Uncertainty Principle.

In a survey of the teachers following the workshop, 96.71% of respondents rated the program as excellent (63.74%) or good (32.97%). 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 14 teachers. 98.9% of respondents said that they would actively encourage people to apply (75.82%) or if asked, they would encourage people to apply (23.08%).

“The classes bring a creative and efficient approach to learning Quantum Mechanics. The materials are impeccable: slides with animations of quantum phenomena, explanatory figures and appropriate and accessible language for the target audience. It is impossible not to like the classes, they are simply wonderful! I would participate in the class every year if it were possible. In addition, I will multiply the knowledge acquired and deepened with my students here in my country (Brazil). It was perfect!”

“The design of the workshop was creative. It had a particular reflective framework. The topics were very interesting, which will allow students to be drawn to quantum mechanics and its applications. The dynamics

implemented allowed us to share our reflections and promote a comprehensive discussion with other teachers about the theory behind it. The documentation provided presents very attractive activities, which facilitate implementation in the classroom.”

Public Lectures

This year, IQC launched the ‘Fireside Chat’ series on YouTube, a monthly series of live virtual interviews with IQC researchers and alum which invited the public to learn more about research and career pathways in quantum information. Eight chats were hosted in this fiscal year, with over 300 live viewers and 4000+ on-demand viewers. The high viewership record contributed to our substantial growth in YouTube subscribers. The eight individuals that were featured in this series were:

- Twesh Upadhyaya, IQC graduate student and QCSYS alumnus
- Chris Ferrie, IQC PhD alumnus
- David Gosset, IQC associate professor
- Kristine Boone, IQC PhD candidate
- Raymond Laflamme, IQC professor and former executive director
- Shayan Majidy, IQC PhD candidate
- Shohini Ghose, IQC affiliate
- Thomas McConkey, IQC alumnus

In November, IQC also hosted a public lecture by Katanya Kuntz, a research associate with the Quantum Encryption and Science Satellite (QEYSSat) project titled “Quantum + Space”. This lecture was attended by over 120 live participants and has since accumulated over 2000 views as of March 31, 2021.

Further, IQC’s outreach professionals presented virtual public lectures in partnership with Association Quantum, a quantum awareness network based in Toronto, as well as to life-long learning organizations and alumni associations in Ontario. They also hosted a virtual screening of the Quantum Shorts film festival in collaboration with the National University of Singapore, Wilfrid Laurier University and local cinemas.

High School Visits

Starting in May 2020, IQC has offered 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. The virtual class visits reached over 800 students this year across Ontario, Quebec, Alberta, and Manitoba, as



well as the US and Brazil. Additionally, over 200 middle-school students in Alberta were reached through a partnership with Skype-A-Scientist.

Promoting Science for Women & Girls

Promoting science to women and girls is also a key priority for IQC. Initiatives include providing opportunities for women to network with other women in science through events like our sponsorship and hosting a graduate booth at the Canadian Conference for Undergraduate Women in Physics.

On March 3, 2021, IQC, in partnership with UWaterloo's FemPhys group, hosted an online mentoring event for undergraduate and graduate students at the University of Waterloo. Mentors, all women, some of minoritized identities with backgrounds in STEM, shared their experiences to inspire the upcoming generations of scientists and people in STEM.

Later the same month, IQC also held a virtual panel discussion titled 'Careers in Quantum in STEM', featuring all female panellists. The panel showcased various opportunities that these women had seized on in their careers as well as some of the obstacles that they had faced. Live and on-demand viewers totaled 1300. The panellists featured were:

- Na Young Kim, Associate Professor at IQC and Electrical and Computer Engineering
- Kristine Boone, IQC: UWaterloo PhD candidate, Quantum Information
- Adele Newton, CS-Can|Info-Can executive director, former IQC staff

As part of the IQC 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 QCSYS (high school students) had 30% female-identifying applicants and 36% female-identifying invitees, while Schrödinger's Class (high school teachers) had 38% female-identifying applicants and 44% female-identifying invitees. By helping girls and young women to see themselves in quantum information science, 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 Royal Canadian Institute for Science and Youth Science Canada to bring quantum to virtual public spaces. IQC has also partnered with local businesses including the Apollo Cinema to co-host virtual events, such as a special screening of quantum-themed short films. IQC also has existing relationships with TelusSpark and Canadian Association for Girls in Science (CAGIS) and remains committed to engaging with corporate and non-profit partners to promote quantum science everywhere. We are focused on building new partnerships in FY2021-2022, some of which have already begun to flourish.



Communications

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

New Stories and Earned Media

With research results reported on each year, IQC strives to promote its community's work to the mainstream media. This year, approximately 308 media mentions of IQC were recorded, translating to a reach of 1.4 billion impressions (the number of times that a post has been viewed on a feed). While the number of media mentions has declined from FY2019-2020, the mentions have occurred in outlets with greater potential reach, increasing the impressions per mention.

Media outlets include (but are not limited to): the National Post, CBC, Forbes, The Independent, Yahoo! Finance, the International Business Times, Businesswire, University Affairs, the National Observer and the Hindustan Times. All mentioned or cited IQC or IQC researchers in the last year, demonstrating IQC's global presence in this emerging and international quantum industry.

Print Publications


In June 2020, IQC launched the 2019 Impact Report. The report is a redesigned and refocused version of the former Annual Report that highlights the exciting developments and potential applications of the work of our researchers with simple, clear storytelling and accessibly presented data.

After a delay caused by the onset of the global pandemic, IQC mailed the print version of the 2019 Impact Report to over two hundred recipients at the university, in the community, and in government. Also, copies are on campus and are available to IQC members for stakeholder relations and distribution. The highly visual and engaging nature of the redesigned 2019 Impact Report and its attention-grabbing packaging was intended to capture the attention of key audiences and remind them of the ongoing importance of quantum information science and technology research. This publication won the CASE (Council for Advancement and Support of Education) silver medal. This is a testament to hard work and high standards in communicating IQC's achievements.

During this same period, planning began for the 2021 Impact Report, which will be a primarily digital production with a smaller print run to showcase the relevance of IQC research for Canada to key stakeholders.

Website

IQC's website is a key medium for sharing IQC's knowledge, research, success, and increasing awareness of IQC as a world leader conducting research on quantum technologies.



Traffic to the IQC website remained consistent with the previous reporting period for most of the year with one exception. In late October of 2019, Google's publication of its quantum supremacy paper ("Quantum Supremacy using a programmable superconducting processor", Nature, October 23, 2019) and the mass media coverage that followed resulted in a large spike in organic search traffic to the IQC website. This spike demonstrated that the IQC website is an important and authoritative source for those looking to make sense of quantum information science in the headlines. That irregular spike in traffic represented thousands of new users to the website, which was not replicated in October 2020. As a result, the traffic to IQC's website decreased slightly in the reporting period compared to the previous year – there were 108,510 unique visitors in FY2020-21 compared to 119,641 in FY2019-2020.

It will be important to monitor web traffic in the next reporting period to measure the impact of the website redesign and the impending publication of the new 'Quantum 101' section, both of which will be described later in this section.

Approximately 74% of web traffic in the reporting period is from outside Canada, with visitors from India, China and the United Kingdom representing the largest proportion of new international visitors. Organic search was responsible for 59% of the traffic to the IQC website during the reporting period, meaning that the majority of IQC's visitors found the website by using search engines. The query "quantum computing" was the single biggest driver of traffic to the website, indicating that IQC is an important and authoritative search result for those looking to learn more about this quantum application.

To improve audiences' online experience and the SEO rankings even further, the IQC redesigned website components, including the menu structure, and relaunched or updated most website pages. IQC is now in the process of designing and creating a new section of the website called 'Quantum 101', which will be a more engaging, accessible and informative web experience to replace the current page 'Quantum Computing 101' and will be launched in the next reporting period.

This new experience will be advertised through paid and organic social media posts and featured prominently on the main page of the website. Tracking the performance of this new context experience and the website redesign will be a priority over the next year to evaluate and increase the performance of the redesign.

In addition to the revamping of the current website, IQC also launched a new digital publications website for the 2019 Impact Report in [English](#) and [French](#), which featured the stories and other key content of the printed report. The digital publication increased the external reach of the report by roughly five-fold as it attracted 1,344 users and 5,148 page views during the reporting period.

Before launching the digital publications site, performance metrics were set to measure the ability of the site to encourage people to read about the impact of IQC's research in quantum information science and technology on Canada and the world. The results showed online 2019 Impact report scored well above-average engagement relative to industry benchmarks.

Social Media

IQC continued to post informative and engaging content on social media for its followers throughout April 1, 2020 to March 31, 2021. Nearly 700 pieces of content posted across Facebook, Twitter and Instagram generated 1.17 million impressions and 8,167 interactions. During the same period, the IQC YouTube channel garnered over 240,000 views and over 33,000 hours of watch time.

IQC drew particular attention to IQC researchers' accomplishments and impact with a dedicated Impact Report campaign across Facebook, Twitter and Instagram. This campaign consisted of 89 social media posts generating 117,830 impressions and 1,257 interactions, including hundreds of clicks leading to the digital publication.

Throughout last year IQC enjoyed steady growth across all its social media platforms. Below are some highlights of social platform growth from April 1, 2020 to March 31, 2021.

	New Followers	Total Current Followers	Increase
YouTube	3,837	21,400	21.9%
Facebook	132	5,432	2.5%
Twitter	1,597	15,300	11.7%
Instagram	297	1,189	33.3%

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 new strategies to generate quantum-related social media content that is valuable for IQC's audiences and to use new features and opportunities to expand the reach of IQC's content. With valuable content that reaches an ever-growing audience, IQC will be able to continue 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 E

Increase translating research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada, thereby enhancing partnerships and collaborations with private sector partners and commercialization opportunities.

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 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 start-up networks in Waterloo Region

Supporting Quantum Industry and Ecosystem Connections

IQC is a critical player in the quantum science, technology, and innovation ecosystem in Canada. It continues to foster an environment of entrepreneurship, and it brings academics, start-up companies, incubators, and investors together to accelerate the commercialization of quantum technology.

As of March 2021, IQC researchers collectively held over 40 patents and 30 licenses including three new patents granted in 2020-2021⁴. Currently, IQC faculty have 45 active patent applications pending approval.

IQC's research and innovative new technologies are spinning out into companies and into the marketplace. To date, the below sixteen startups have emerged from IQC research.

⁴ Reduction in total number of patents, Pending and Active, is due mainly to change in status of granted patents to 'Expired' and/or 'Ceased'

IQC quantum spin-off companies:

- EvolutionQ
- Neutron Optics
- QuantumLaf Inc.
- Universal Quantum Devices
- SoftwareQ Inc
- SpinQ
- Aquabits
- Northern Quantum Lights
- High Q Technologies LP
- Quantum Benchmark Inc.
- QuSpin Technologies Inc.
- Single Quantum Systems
- QEYnet
- Everettian
- Q-Block Computing Inc.
- Aegis Quantum

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 30%+ of IQC principal investigators have commercialized their expertise and research through spin-off companies and patents, more are supporting the development of a quantum industry in other ways. These additional contributions include advising 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 the Quantum Valley.

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. Further, this unique environment combined with programs like the Quantum Alliance Program has led to several technological applications. Highlights include:

- Commercializing tools for characterizing and validating quantum processors with enhancements (Joseph Emerson, Quantum Benchmark).
- Transitioning out of the lab a novel quantum material to detect single photons and building the control electronics needed to bring this sensor to applications including defence and health (Michael Reimer, Single Quantum Systems).
- Developing new quantum structure invisible to the naked eye and printed directly on government documents (e.g., banknotes) to replicate security feature (Michal Bajcsy, IQC).
- Pioneering new structural biology tools that for the first time allows the direct study of protein structure in membranes (David Cory, High Q Technologies LP).

- Exploring the impact of quantum on logistics processes with government and industry partners (Jon Yard, IQC).

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 begun to partner with different ecosystem partners in the Quantum Valley and in the Waterloo-Toronto tech corridor to establish relationships with different stakeholders.

- In January 2021, IQC partnered with Velocity, an incubator for early-stage, pre-seed technology startups from the University of Waterloo and around the world, to host an information session on the Velocity program. The information session is just the first of a planned seminar series between IQC and Velocity aimed at IQC students and researchers to help empower their decisions to commercialize their research.
- In May 2021, IQC partnered with Creative Destruction Lab to highlight its Quantum program stream aimed at helping early-stage quantum startups grow and develop a pitch ready prototype. The seminar was in partnership with TQT and Perimeter Institute and allowed the respective institutes and programs to highlight to the audience of students, researchers and primary investigators the different ways aspiring entrepreneurs could find support in the Quantum Valley.
- IQC met with Raiven Capital in February 2021 and Good News Ventures in August 2020 to initiate conversation about defining relationships with Canadian-based venture firms. These conversations were seen as the first conversation to introduce these firms to IQC's flourishing quantum startup ecosystem. Both firms requested in-person visits to the IQC campus when travel was allowed again. Further conversation will continue in 2021/2022.

B. Publications

April 1, 2020-March 31, 2021

1. Adjei, E; Resch, KJ; Branczyk, AM. (2020) Quantum simulation of Unruh-DeWitt detectors with nonlinear optics. *Physical Review A*
2. Agne, S; Jin, J; Kuntz, KB; Miatto, FM; Bourgoïn, JP; Jennewein, T. (2020) Hong-Ou-Mandel interference of unconventional temporal laser modes. *Optics Express*
3. Agusti, A; Chang, CWS; Quijandria, F; Johansson, G; Wilson, CM; Sabin, C. (2020) Tripartite Genuine Non-Gaussian Entanglement in Three-Mode Spontaneous Parametric Down-Conversion. *Physical Review Letters*
4. Al Maruf, R; Bharadwaj, D; Anderson, P; Qiu, JW; Zeeshan, M; Poole, P; Dalacu, D; Reimer, M; Bajcsy, M. (2020) High Efficiency Fiber-Coupled Single-Photon Source Based on Quantum Dot Embedded in a Semiconductor Nanowire. 2020 Conference On Lasers And Electro-Optics (Cleo)
5. Albrecht, M.R., Gheorghiu, V., Postlethwaite, E.W., Schanck, J.M.. (2020) Estimating Quantum Speedups for Lattice Sieves. *Lecture Notes In Computer Science (Including Subseries Lecture Notes In Artificial Intelligence And Lecture Notes In Bioinformatics)*
6. Alhambra, AM; Anshu, A; Wilming, H. (2020) Revivals imply quantum many-body scars. *Physical Review B*
7. Allgaier, M; Ansari, V; Donohue, JM; Eigner, C; Quiring, V; Ricken, R; Brecht, B; Silberhorn, C. (2020) Pulse shaping using dispersion-engineered difference frequency generation. *Physical Review A*
8. Amy, M; Gheorghiu, V. (2020) staq-A full-stack quantum processing toolkit. *Quantum Science And Technology*
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12. Anshu, A. (2020) Improved local spectral gap thresholds for lattices of finite size. *Physical Review B*
13. Anshu, A; Arad, I; Gosset, D. (2020) Entanglement Subvolume Law for 2D Frustration-Free Spin Systems. *Proceedings Of The 52Nd Annual Acm Sigact Symposium On Theory Of Computing (Stoc '20)*
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