IQC Institute for Quantum Computing

Annual Report
April 1, 2019 – March 31, 2020

For submission to the Ministry of Innovation, Science and Economic Development
July 31, 2020

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

FROM THE EXECUTIVE DIRECTOR

Canada's Quantum Future

This past year was another productive one for the Institute for Quantum Computing (IQC). Thanks to the continued, generous support from the Government of Canada, IQC was able to continue as a world leader in quantum research collaborations, infrastructure and education. We attracted leading researchers to IQC to build their careers, collaborate and train the next generation of quantum experts.

IQC's unique setting has allowed us to build a truly interdisciplinary research community of scientists, mathematicians and engineers that work to explore opportunities in quantum computing, communications, sensing and materials. These quantum technologies will revolutionize some of the largest industrial sectors in the world: health and medicine, natural resources, environmental monitoring, cybersecurity, electronics, and telecommunications. Research conducted at IQC has connected quantum properties to important applications from communications security to new techniques in cancer treatments. We have developed quantum algorithms and methods for optimizing the performance of quantum computers. We expanded the theory of quantum communication and developed new techniques essential for Canada's quantum satellite mission. We continue to work with industry to develop new ways of solving some of the most challenging problems the world is grappling with today.

As IQC continues work to recruit an additional seven principal investigators to reach its full complement, we must acknowledge the competition for top global talent is fierce as other countries and multinational corporations ramp up their investments and activities in quantum. However, Canada's early investment in this area established a resourced and vibrant research environment making Waterloo Region a compelling place for the world's best quantum experts. Alongside efforts in research, recruitment and training, IQC has also worked to develop new initiatives to support industrial growth and we are expanding our training options to meet the demands of the quantum workforce.

The quantum revolution is here and I'm proud that IQC and Canada are playing a leading role.

Kevin Resch Interim Director
Institute for Quantum Computing
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, last year 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 2019-2020 year, include:

- Attracted over $30,000,000 in research funding
- Recruited two new faculty members
- Recruited six new research associates
- Published over 170 papers in peer-reviewed journals
- Reached over 47,500 cumulative citations
- Recruited 29 new postdoctoral fellows
- Received over 400 awards received by IQC graduate students
- Reviewed 500+ applications to graduate programs, including 15% from women
- Hosted 141 longer-term, scientific visitors from 100 unique institutions globally
- Hosted three major conferences, six workshops, 60 seminars and 21 colloquia, and sponsored 14 external scientific programs
- Partnered with the Centre for Quantum Technologies to host QUANTUM: The Exhibition in Singapore where over 200,000 people visited it
- Engaged by an intelligence agency to give an expert briefing to 80 invited guests from across government and to close-door meetings with security officials

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 quantuminformation.
3. To be a prime source of insight, analysis and commentary on quantuminformation.

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 2019-2020 year.

ACHIEVEMENTS 2019-2020

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:

- Leverage faculty across three 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
- Continue to publish research results in world-leading journals
- Recruit new faculty members
- Recruit new research assistant professors
- Continue to outfit labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre as new IQC members are recruited
- Continue to outfit and maintain the Quantum Nano Fabrication and Characterization Facility to enable fabrication of quantum-enabled technologies
- Continuing the update and maintenance of lab space in the Research Advancement Centre (RAC) buildings
- Continue effective and relevant relationships with current research partners
- Seek out new partnerships that will advance IQC's mission and strategic objectives

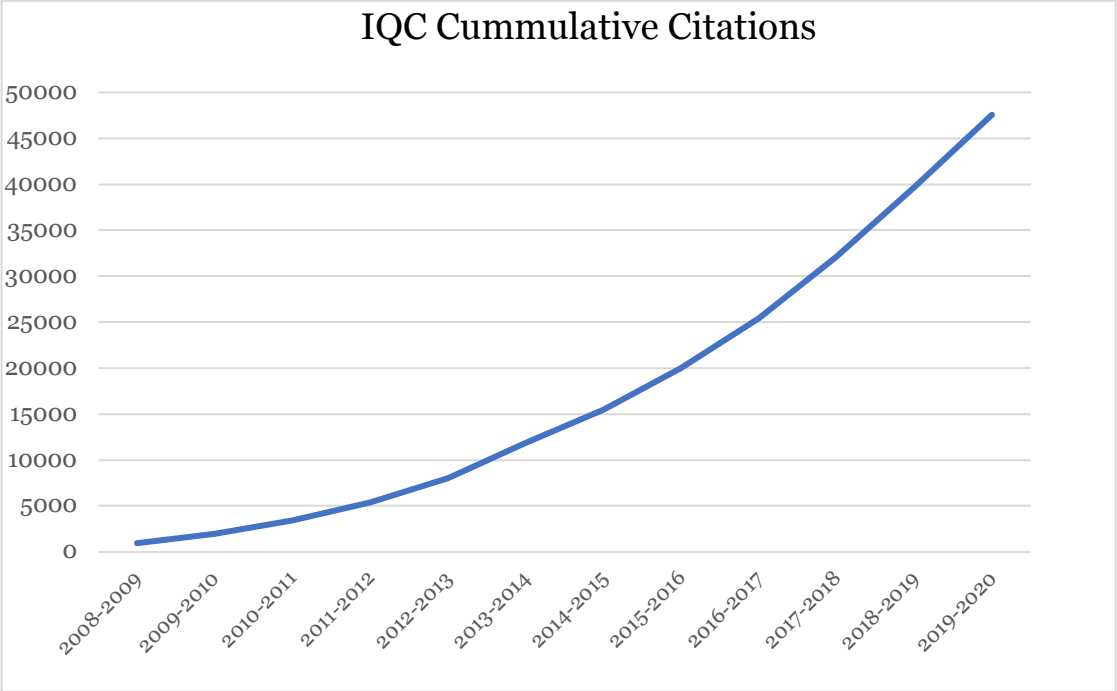
Research Publications & Citations

In 2019-2020, IQC researchers collectively published 171 papers in peer-reviewed journals bringing the cumulative number of publications to 1,922 since 2002. Several papers appear in prominent scientific publications including journals in Science, the Nature family, the Journal of Mathematical Physics and Physical Review Letters. Below is a summary of articles published in prominent journals since 2013. A full list of all papers published this year can be found in Appendix B beginning on page 48.

Prominent Publications	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Family of Nature Journals	7	9	7	9	6	4	8
Physical Review Letters	14	16	17	11	6	8	15
Science	1	3				1	
Journal of Mathematical Physics	4	4	6	2	3	3	2
FOCSs			1				3
STOC					1	1	

Further analysis reveals that 69% 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.

Citations are also an important indicator of the influence of the of research published. As of March 31, 2020, the number of cumulative citations from IQC's published papers reached 47,564. 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; timespan FY2008-2009 to FY2019-2020. Data pulled on March 31st of each fiscal year.*

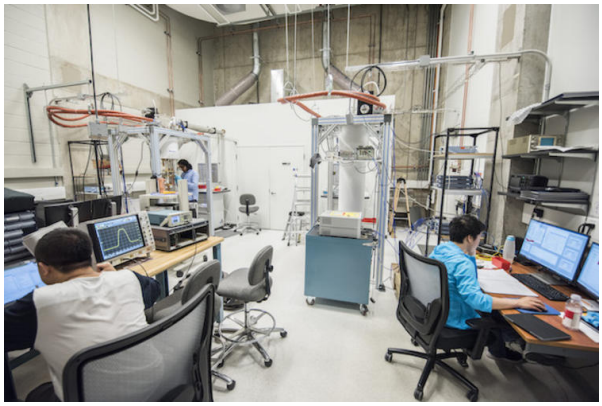
Research Highlights

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.

OBSERVATION OF THREE-PHOTON SPONTANEOUS PARAMETRIC DOWN-CONVERSION IN A SUPERCONDUCTING PARAMETRIC CAVITY
Published in Physical Review X on January 16, 2020
https://journals.aps.org/prx/abstract/10.1103/PhysRevX.10.011011

Researchers from IQC reported the first occurrence of directly splitting one photon into three.

The occurrence, the first of its kind, used the spontaneous parametric down-conversion method (SPDC) in quantum optics and created what quantum optics researchers call a non-Gaussian state of light. A non-Gaussian state of light is considered a critical ingredient to gain a quantum advantage.



Students working in Chris Wilson's lab.

"It was understood that there were limits to the type of entanglement generated with the two-photon version, but these results form the basis of an exciting new paradigm of three-photon quantum optics," said CHRIS WILSON, a principal investigator at IQC, faculty member and a professor of Electrical and Computer Engineering at Waterloo.

"Given that this research brings us past the known ability to split one photon into two entangled daughter photons, we're optimistic that we've opened up a new area of exploration."

"The two-photon version has been a workhorse for quantum research for over 30 years," said Wilson. "We think three photons will overcome the limits and will encourage further theoretical research and experimental applications and hopefully the development of optical quantum computing using superconducting units."

Wilson used microwave photons to stretch the known limits of SPDC. The experimental implementation used a superconducting parametric resonator. The result clearly showed the strong correlation among three photons generated at different frequencies. Ongoing work aims to show that the photons are entangled.

"Non-Gaussian states and operations are a critical ingredient for obtaining the quantum advantage," said Wilson. "They are very difficult to simulate and model classically, which has resulted in a dearth of theoretical work for this application."

ASYMPTOTIC SECURITY ANALYSIS OF DISCRETE-MODULATED CONTINUOUS-VARIABLE QUANTUM KEY DISTRIBUTION

Published in Physical Review X on December 30, 2019
https://journals.aps.org/prx/abstract/10.1103/PhysRevX.9.041064

IQC researchers have developed a new tool for evaluating the security of a broad class of protocols that can take advantage of existing telecom infrastructure to deploy large quantum-secured communication networks in the near future.

Quantum computing poses a threat to our current cryptographic infrastructure. Quantum key distribution (QKD) is expected to be an important part of the solution to this problem by allowing two distant parties to establish long strings of digits, called keys, which are secured using the laws of quantum mechanics.

These secret keys can then be used in other cryptographic systems for secure communication, authentication and other cryptographic applications. New research by IQC PhD student JIE LIN, Master's student TWESH UPADHYAYA and professor in the Faculty of Science's physics and astronomy department NORBERT LÜTKENHAUS demonstrates the security of a class of QKD protocols that could be both practical and affordable for widespread adoption on our current telecommunications networks.

The main theoretical problem in QKD is calculating the key rate of QKD protocols, which reveals how efficiently they operate. Many protocols that have already been established as theoretically secure are so-called discrete-variable QKD protocols. They encode quantum information in distinct quantum states of photons, and require advanced single photon detectors to receive the key. These protocols, while easier to analyze theoretically, have a higher hurdle to be adopted widely: they would require augmenting existing telecommunications infrastructure with specialized, separate technology.

PhD student Jie Lin, Master's student Twesh Upadhyaya, and faculty member Norbert Lütkenhaus.

An alternative to discrete-variable QKD is continuous-variable QKD (CVQKD), which allows the information in a secret key to be encoded in continuous variables like the amplitude of an optical signal sent through a fiber cable. The technology to receive this kind of quantum information is already widely used in the high-speed telecommunications networks that keep us connected, thus lowering the threshold for CVQKD compared to the discrete-variable protocols. This makes CVQKD a promising candidate for the widespread adoption of secure quantum networks.

Previous studies of CV protocols required these encoding quantum states to be randomly chosen from a huge set of states according to a continuous distribution in order to guarantee the security. However, the accurate and fast preparation of the states, the demand on the amount of randomness generated, and the computational and communication power required for this type of protocols poses a challenge to widespread adoption.

In this new research, IQC researchers studied a class of CVQKD protocols that only require a small number of quantum states. These protocols combine the advantages of discrete variable protocols (low requirement on random number generation, low computational power for processing of data) with that of CVQKD, namely sharing the optical technology with modern

optical communication equipment that is deployed today. So far, however, the theoretical security and rate analysis of these protocols has been missing as they are more challenging to do than previously studied protocols.

The researchers developed a method to prove the security of this type of CVQKD protocols and determine the secure key rate. Their method of analysis is versatile, meaning that it can be used to evaluate a variety of useful CVQKD protocols.

The work builds on previous research by Lütkenhaus' Optical Quantum Communication Theory Group that developed an easy-to-use software tool to evaluate many QKD protocols. The new research extends the tool to highly promising CVQKD protocols compatible with mainstream telecommunications infrastructure.

The combination of security, versatility and practicality means that CVQKD protocols are a cost-effective way to secure our vital information with secret keys in future quantum communications networks.

NEW MIRROR MADE FOR QUANTUM RESEARCH COULD CATCH COUNTERFEIT CASH

The paper Spin-preserving chiral photonic crystal mirror was published in Light Science and Applications by Nature Publishing Group on February 20, 2020
http://www.nature.com/articles/s41377-020-0256-5

Researchers at 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).

PROPOSED SCHEME TO GENERATE BRIGHT ENTANGLED PHOTON PAIRS BY APPLICATION OF A QUADRUPOLE FIELD TO A SINGLE QUANTUM DOT
Published in Physical Review Letters on June 7, 2019
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.227401

Entangled photon sources are crucial for quantum optics, quantum sensing, and quantum communication. Semiconductor quantum dots generate on-demand entangled photon pairs via the biexciton-exciton cascade. However, the pair of photons are emitted isotropically in all directions, thus limiting the collection efficiency to a fraction of a percent. Moreover, strain and structural asymmetry in quantum dots lift the degeneracy of the intermediate exciton states in the cascade, thus degrading the measured entanglement fidelity. Here, MICHAEL REIMER and colleagues propose an approach for generating a pair of entangled photons from a semiconductor quantum dot by application of a quadrupole electrostatic potential. We show that the quadrupole electric field corrects for the spatial asymmetry of the excitonic wave function for any quantum dot dipole orientation and fully erases the fine-structure splitting without compromising the spatial overlap between electrons and holes. Our approach is compatible with nanophotonic structures such as microcavities and nanowires, thus paving the way towards a deterministic source of entangled photons with high fidelity and collection efficiency.

BENCHMARKING SCALABILITY AND PERFORMANCE OF QUANTUM COMPUTERS
The paper Characterizing large-scale quantum computers via cycle benchmarking was published in Nature Communications on November 25, 2019
https://www.nature.com/articles/s41467-019-13068-7

Researchers at IQC have demonstrated a new method, called cycle benchmarking, to assess scalability and compare capabilities of different quantum computer platforms. The finding leads the way towards establishing standards for quantum computing performance and strengthens the global effort to build a large-scale, practical quantum computer.

IQC faculty members Joel Wallman and Joseph Emerson at the offices of Quantum Benchmark

"A consistent method for characterizing and correcting the errors in quantum systems provides standardization for the way a quantum processor is assessed, allowing progress in different architectures to be fairly compared," said JOEL WALLMAN, Assistant Professor at IQC and the Department of Applied Mathematics at the University of Waterloo.

Cycle benchmarking provides a solution that helps quantum computing users determine the comparative value and increase the capability of any hardware platform to deliver robust solutions for their applications of interest. The breakthrough comes as the quantum computing race is rapidly heating up and the number of cloud quantum computing platforms and offerings is rapidly expanding. Recently, there have been major announcements from Microsoft, IBM and Google.

This method also determines the probability of an error under various quantum computing applications, when the application is implemented through randomized compiling. This means that cycle benchmarking provides a cross-platform means of measuring and comparing the capabilities of quantum processors offered from different providers, in a way that can be customized to users' applications of interest.

"Cycle benchmarking unlocks the door to assessing, improving and validating quantum computing capabilities in the current era of quantum discovery, where error-prone quantum computers hope to deliver new solutions to pressing problems and the quality of these solutions that can no longer be verified by high-performance computers," says JOSEPH EMERSON, faculty member at IQC and the applied mathematics department and co-author of the study.

Emerson and Wallman founded the IQC spin-off Quantum Benchmark Inc., which has already licensed this technology to several world-leading quantum computing providers, including Google's Quantum AI effort.

The error problem

Quantum computers offer a fundamentally more powerful way of computing, thanks to quantum mechanics. Compared to a traditional or digital computer, quantum computers can solve certain types of problems more efficiently. However, qubits—the basic processing unit in a quantum computer—are fragile; any imperfection or source of noise in the system can cause errors that lead to incorrect solutions under a quantum computation.

Gaining control over a small-scale quantum computer with just one or two qubits is the first step in a larger, more ambitious endeavour. A larger quantum computer may be able to perform increasingly complex tasks, like machine learning or simulating complex systems to discover new pharmaceutical drugs. Engineering a larger quantum computer is challenging; the spectrum of error pathways becomes more complicated as qubits are added and the quantum system scales.

To scale or not to scale

Characterizing a quantum system produces a profile of the noise and errors, indicating if the processor is actually performing the tasks or calculations it is being asked to do. To understand the performance of any existing quantum computer for a complex problem or to scale up a quantum computer by reducing errors, it's first necessary to characterize all significant errors affecting the system.

Wallman, Emerson and a group of researchers at the University of Innsbruck identified a method to assess all error rates affecting a quantum computer. They implemented this new technique for the ion trap quantum computer at the University of Innsbruck, and found that error rates don't increase as the size of that quantum computer scales up, a very promising result.

"Cycle benchmarking is the first method for reliably checking if you are on the right track for scaling up the overall design of your quantum computer," said Wallman. "These results are significant because they provide a comprehensive way of characterizing errors across all quantum computing platforms."

NOVEL TECHNIQUE FOR ROBUST OPTIMAL ALGORITHMIC COOLING
Published in Physical Review Letters on June 7, 2019
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.220501

Heat-bath algorithmic cooling provides algorithmic ways to improve the purity of quantum states. These techniques are complex iterative processes that change from each iteration to the next and this poses a significant challenge to implementing these algorithms. Here, Sadegh Raeisi, Mária Kieferová, and MICHELE MOSCA introduce a new technique that on a fundamental level, shows that it is possible to do algorithmic cooling and even reach the cooling limit without any knowledge of the state and using only a single fixed operation, and on a practical level, presents a more feasible and robust alternative for implementing heat-bath algorithmic cooling. We also show that our new technique converges to the asymptotic state of heat-bath algorithmic cooling and that the cooling algorithm can be efficiently implemented; however, the saturation could require exponentially many iterations and remains impractical. This brings heat-bath algorithmic cooling to the realm of feasibility and makes it a viable option for realistic application in quantum technologies.

QUANTUM CLOUD COMPUTING WITH SELF-CHECK: NEW METHOD ENABLES POWERFUL QUANTUM SIMULATION ON CURRENT HARDWARE
The paper Self-verifying variational quantum simulation of lattice models was published in Nature on April 3, 2019
https://www.nature.com/articles/s41586-019-1177-4

A quantum co-processor successfully simulated particle physics phenomena on 20 quantum bits and self-verified the result for the first time, according to a new study published in Nature.

The experiment, conducted by a team of researchers in Innsbruck, Austria including Rainer Blatt, Peter Zoller and IQC faculty member CHRISTINE MUSCHIK, opens the door to the simulation of previously unsolvable problems in chemistry, materials research and high-energy physics.

“With this new type of quantum simulator, we will investigate and deepen our understanding of high energy and particle physics, including questions about the early universe,” said Muschik, also an assistant professor in the Department of Physics and Astronomy at the University of Waterloo.

Many scientists are currently working on investigating how quantum advantage can be exploited on hardware already available today. Three years ago, a team including Muschik, Blatt and Zoller first simulated the spontaneous formation of a pair of elementary particles with a digital quantum computer at the University of Innsbruck. Due to the error rate, however, more complex simulations would require a large number of quantum bits that are not yet available in today's quantum computers. The analog simulation of quantum systems in a quantum computer also has narrow limits.

Using a new method, researchers at the Institute of Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences have now surpassed these limits. They used a programmable ion trap quantum computer with 20 quantum bits as a quantum co-processor, in which quantum mechanical calculations that reach the limits of classical computers are outsourced.

"We use the best features of both technologies," explained experimental physicist Christine Maier. "The quantum simulator takes over the computationally complex quantum problems and the classical computer solves the remaining tasks."

Toolbox for Quantum Modelers

The scientists used the variational method known from theoretical physics, but applied it on their quantum experiment. "The advantage of this method lies in the fact that we can use the quantum simulator as a quantum resource that is independent of the problem under investigation," explains Rick van Bijnen. "In this way we can simulate much more complex problems."

A simple comparison shows the difference: an analog quantum simulator is like a doll's house; it represents reality. The programmable variational quantum simulator, on the other hand, offers individual building blocks with which many different houses can be built. In quantum simulators, these building blocks are entanglement gates and single spin rotations. With a classical computer, this set of knobs is tuned until the intended quantum state is reached. For this, the physicists have developed a sophisticated optimization algorithm that, after about 100,000 uses of the quantum co-processor by the classical computer, leads to the result.

Coupled with extremely fast measurement cycles of the quantum experiment, the simulator at IQOQI Innsbruck becomes enormously powerful. The physicists have simulated the spontaneous creation and destruction of pairs of elementary particles in a vacuum on 20 quantum bits. Since the new method is very efficient, it can also be used on even larger quantum simulators. The researchers plan to build a quantum simulator with up to 50 ions in the near future. This opens up interesting perspectives for further investigations of solid- state models and high-energy physics problems.

Built-in Self-Check

A previously unsolved problem in complex quantum simulations is the verification of the simulation results. "Such calculations can hardly or not at all be checked using classical computers. So how do we check whether the quantum system delivers the right result," said theoretical physicist Christian Kokail. "We have solved this question for the first time by making additional measurements in the quantum system. Based on the results, the quantum machine assesses the quality of the simulation," explained Kokail. Such a verification mechanism is the prerequisite for even more complex quantum simulations, because the necessary number of quantum bits increases sharply.

"We can still test the simulation on 20 quantum bits on a classical computer, but with more complex simulations this is simply no longer possible," said Rick van Bijnen. "In our study, the quantum experiment was even faster than the control simulation on the PC. In the end, we had to take it out of the race in order not to slow down the experiment," said van Bijnen.

The work now published in Nature was financially supported by the Austrian Science Fund FWF and the European Union, among others.

REVEALING QUANTUM GRAVITY WITH QUANTUM COMPUTER SIMULATION

The paper Measuring holographic entanglement entropy on a quantum simulator was published in npj Quantum Information on April 23, 2019
https://www.nature.com/articles/s41534-019-0145-z

RAYMOND LAFLAMME, Department of Physics and Astronomy professor at IQC at the University of Waterloo, keeps himself curious by exploring new areas of interest.

Working with a team of international researchers, Laflamme, the Mike and Ophelia Lazaridis John von Neumann Chair in Quantum Information, has published his recent findings on simulating a property in quantum gravity on a quantum processor. Laflamme is energized by the finding because quantum gravity has, up until now, been mainly theoretically-based. "We haven't explored [quantum gravity] on a quantum computer before in part because we haven't had a quantum information processor to use," he said.

Laflamme and his team simulated the property characterized by the Ryu-Takayanagi (RT) formula that appears in the field of quantum gravity using a nuclear-magnetic resonance (NMR) quantum processor. Gravity is a force of nature; the other three forces of nature (strong nuclear, weak nuclear and electromagnetic force) have all been well documented in quantum theory. Gravity has not fit as easily into quantum theory, Laflamme notes, because it is a weaker force of nature compared to the other three, and thus harder to characterize behaviour at the quantum level.

The research, conducted in IQC's nuclear magnetic resonance lab, used a small quantum processor to make a manipulation of the RT formula and then examine the property to see if obeys a relationship that theorists have predicted. Laflamme was pleased with the findings.

"We were able to show the results," he said. "If we had a perfect quantum computer the answer would have been a yes." Due to the noise detected in the quantum processor, Laflamme's finding did not perfectly match the theorized curve of the equation, but it was close enough that it showed that the property was respected when manipulated in a simulation.

"In some sense what we are really doing is asking, do we have enough control on a quantum processor to be able to make simulations that could relate to quantum gravity," he said. "If the answer is no then we had better go back and get control on our quantum computer."

For Laflamme, the answer was yes: the quantum computer is good enough to start to test theories that have an expected answer. Quantum simulation is rarely a yes/ no output, he notes. Rather it is more like weather simulation where there is room for error, but the errors become fewer the better the technology becomes.

Laflamme is already looking to the future when better quantum computers with more qubits and less noise allow researchers to learn properties of states that classical computers can't compute and that theorists haven't predicted the answers to yet. "This is a first step to ask a question and a first attempt to plunge into the field of quantum gravity, but it's not going to be the last one," he said.

HONEYWELL FUNDING LAUNCHES QEYSSAT INTO ORBIT
Published project update on June 19, 2020
https://uwaterloo.ca/institute-for-quantum-computing/news/honeywell-funding-launches-qeyssat-orbit

When senior citizens use online banking apps to pay their bills, you know the world has gone digital. THOMAS JENNEWEIN, IQC member and professor in Waterloo's department of Physics and Astronomy, has been watching digital communication, like banking, become mainstream. And he's worried about it.

Digital communication methods, used currently to send everything from money transfers to pictures of cats, are not the most secure. Jennewein believes quantum encryption is the key.

Since 2009, he has been the Principal Investigator of the Quantum Encryption and Science Satellite(QEYSSat) initiative. Working with the Canadian Space Agency (CSA), he's been developing and testing prototypes of quantum communicators. His goal is to advance quantum cryptography research by demonstrating ultra-secure quantum communication via global satellites.

Jennewein and his team have led rounds of feasibility testing, even launching a prototype in an airplane to demonstrate ground to sky transfer, all in the name of building a more secure method of sharing information between two people over long distances.

But one major piece has been missing in his research: who will actually put his device into orbit? Last week, his question was answered when the CSA announced a $30 million contract awarded to COM DEV, now a part of the Honeywell family, for the design and implementation phase of QEYSSat. "I'm really excited about this news," Jennewein said. "We are proud to be drawing upon Canadian knowledge and expertise to build this mission."

Scheduled for a 2022 launch, Jennewein and his team can now start taking their ideas and prototypes and move them towards a working satellite capable of quantum key distribution, an ultra-secure method of sharing cryptographic keys.

"Building and testing the satellite will allow us to launch quantum communications in space," said Jennewein. "We will demonstrate ultra-secure key distribution on a global scale and help Canada and the world move towards a new generation of secure communication.

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 two new faculty members to its research community.

After studying physics and mathematics at Harvard University, **Alan Jamison** worked in education. He taught high school physics, precalculus, and creative writing. He then worked for an online education start-up teaching university physics to tens of thousands of students in major universities around the world. Alan finished his B.S. in mathematics at the University of Central Florida in 2007.

He received his M.S. and Ph.D. in Physics from the University of Washington in 2008 and 2014, respectively. He initially studied beyond the Standard Model phenomenology under Ann Nelson. High-energy theory gave way to ultracold atomic physics and a thesis on precision atom interferometry using Bose-Einstein condensates, supervised by Subhadeep Gupta. He also developed the supporting theoretical framework for achieving high precision in these experiments with co-adviser J. Nathan Kutz

from Applied Math. He then joined the group of Wolfgang Ketterle at MIT advising three labs during his time there. This research spanned experiments in ultracold molecules and their chemistry, quantum emulation of spin-orbit coupled systems, and laser cooling exotic lanthanide atoms.

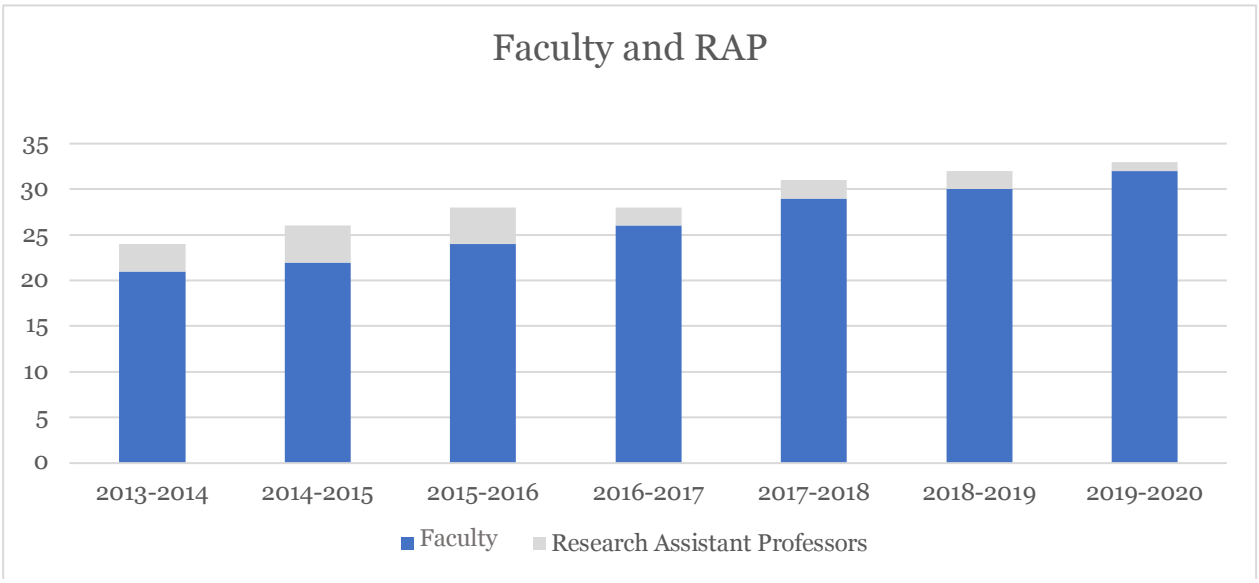
Jamison joined IQC as an Assistant Professor in 2020. His group works on quantum computing and quantum chemistry with ultracold molecules, as well as quantum emulation with ultracold mixtures.

Joel Wallman obtained his BSc (Advanced) in Physics and Mathematics at The University of Sydney (Australia) in 2008 with Honours and was awarded the University Medal for outstanding academic achievement. Wallman completed his PhD in Physics from The University of Sydney (USYD) in 2013 with his thesis titled: Information, Observers, and Quantum Mechanics. He was awarded the Vice-Chancellor's Research Scholarship (USYD) and the Denison Merit award (USYD) for his outstanding track record of academic achievement and research potential.

Wallman completed a postdoctoral research position in 2013 at USYD before moving to the IQC at the University of Waterloo to pursue a postdoctoral position under Dr Joseph Emerson. In 2016 he was awarded a Foundational Questions Institute (FQXi) Physics of the Observer grant.

In 2017, Wallman co-founded the start-up company Quantum Benchmark with Dr. Joseph Emerson and currently holds the position of CTO.

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

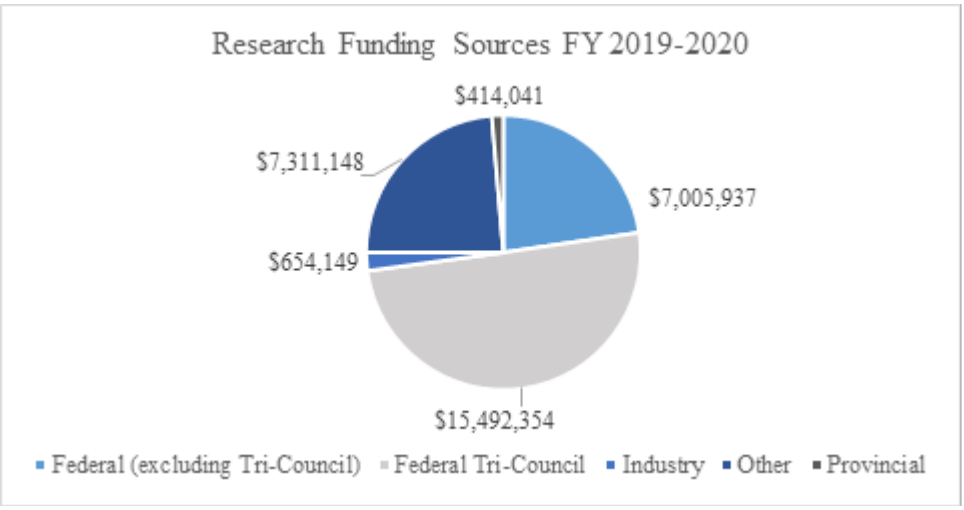


Recruitment – Research Associates

Over the last two years, hiring skilled Research Associates has developed into growing IQC's recruitment plan. Out of a total of ten Research Associates currently part of the IQC complement, six were hired in 2019-2020. Two of the six Research Associates are former IQC postdoctoral fellows, which is a testament to the importance of developing and maintaining the talent pool in Waterloo. These Research Associates work with IQC principal investigators to advance research programs and initiatives. A full list of all 32 current faculty members, one research assistant professor, and ten research associates can be found in Appendix C, beginning on page 57.

Awards & Research Chairs

IQC researchers have collectively been awarded $30,877,629 in research funding during the period April 1, 2019 to March 31, 2020. 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 brief list of awards faculty members received in 2019-2020:

Faculty Member	Award	Source
Adrian Lupascu	Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant	NSERC
Ashwin Nayak	Power and limitations of Quantum Algorithms	Fujitsu Laboratories of America
Christine Muschik	NSERC Discovery Launch Supplement Alfred P. Sloan Research Fellowship in Physics	NSERC Alfred P. Sloan Foundation
Christopher Wilson	NSERC Discovery Grant	NSERC

Faculty Member	Award	Source
David Gosset	NSERC Discovery Grant	NSERC
	Recipient of the TQC2019 Outstanding Paper Prize	TQC2019
	NSERC Discovery Launch Supplement (DGECR)	NSERC
	NSERC Discovery Accelerator Supplement (RGPAS) grant	NSERC
Joel Wallman	US Army Research Office	The Army Research Office, US Army
	University of Waterloo startup grant	The University of Waterloo
John Watrous	NSERC Discovery Grant	NSERC
	CIFAR Fellow Support	CIFAR Fellow Support
Jonathan Baugh	NSERC Engage with Kennedy Labs.	NSERC
	TQT Seed Fund "Materials for Majorana-based topological qubits" (co-PI; main PI is Z. Wasilewski), 2 years	Transformative Quantum Technologies (TQT) - Quantum Quest Seed Fund (QQSF), Canada First Research Excellence Fund
	Co-winner (2019), Best panel session of VTS 2018, "Quantum systems: next challenges in design, test, integration"	IEEE VLSI Test Symposium (VTS)
K. Rajibul Islam	Early Researcher Award, Ontario (2019)	Ontario Ministry of Research, Innovation, and Science
Kevin Resch	NSERC Discovery Grant	NSERC
Kyung Soo Choi	IOF fund	Canadian Foundation for Innovation (CFI)
	IRPG grant	The International Research Partnership Grants (IRPG)
	Waterloo-Bordeaux IdEX funding	University of Waterloo (UW) and the University of Bordeaux (UBx)
Matteo Mariantoni	John R. Evans Leaders Fund (JELF)	CFI
	NSERC Discovery Grant	NSERC
	NSERC Discovery Accelerator Supplement (DAS)	NSERC
	WatCo Prototype Funding	The Waterloo Commercialization Office (WatCo)
Michal Bajscy	TQT Quantum Seed fund Round 4	Canada First Research Excellence Fund, TQT-QQSF
Michele Mosca	Interdisciplinary Trailblazer Fund	University of Waterloo
	Open Quantum Safe (libOQS) Project	Amazon
	Research on Secure and Reliable QKD networks	National Research Council
Wei Tsen	US Army Research Office	The Army Research Office, US Army
	TQT Quantum Seed Round 4	TQT - Quantum Quest Seed Fund (QQSF), Canada First Research Excellence Fund

NB: Due to the internal reporting structure, it is possible there are additional awards not captured in the above chart.

IQC is also home to the following Research Chairs: 52c

- David Cory, Canada Excellence Research Chair Laureate (2017)
- Kevin Resch, Canada Research Chair (2013-2023)
- Raymond Laflamme, Canada Research Chair (2002-2022)
- Michele Mosca, University Research Chair (2012-2022)
- Debbie Leung, University Research Chair (2015-2022)
- Raymond Laflamme, Mike and Ophelia Lazaridis (2017-2027)
- Raffi Budakian, University of Waterloo Endowed Chair in Nanotechnology (2014-2019)

Infrastructure – Mike & Ophelia Lazaridis Quantum-Nano Centre

As of March 2020, there are 16 operational research labs in the Lazaridis Centre, with an additional research lab currently being designed for experiments by IQC's most recently recruited faculty member, Alan Jamison.

In previous reports, IQC shared that Crystal Senko and Rajibul Islam were in the process of setting up their Ion trapping labs. Both labs are now fully operational which is an important first step in enabling IQC researchers to build out quantum simulators, and eventually quantum computing applications. Active research labs in the Lazaridis Centre currently include:

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

Each lab is maintained and updated by respective researchers. One of the more recent experimentalists to join IQC – Alan Jamison – is in the process of designing his lab. The initial renovation designs are with the architectural and consulting firms who are working on detailed designs. Initial electronic and optical components have been ordered as well as a fiber laser system.

Infrastructure – Quantum-Nano Fabrication and Characterization Facility

The newly renamed 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 32,894 hours of independent lab equipment use logged by registered lab users. This is the highest use in one year reported to date and represents a year-over-year growth of 10%.

The facility was actively used by 195 people over the course of the year. Each of these people is affiliated with one of 59 different research groups from across campus and Canada which made use of the QNFCF for their respective research programs this past year.

Over 3,500 hours of process development activities were logged by staff which resulted in the creation and characterization of multiple new processes (and several new technical reports) to the benefit of all registered users of the facility.

Over 900 hours of hands-on equipment user training was provided by staff. In addition, many hundreds of hours of ongoing process support and guidance that is routinely provided by process engineering staff to the facility's entire membership.

The IQC and CFREF-TQT (Transformative Quantum Technologies) programs support the QNFCF operations and in 2019-2020 contributed over $2M to cover staff salaries, lab renovations, new lab equipment acquisitions and equipment service contracts. A handful of popular core lab systems such as the chlorine Reactive Ion Etch (RIE) system were used at near full capacity throughout the year.

Of note, lab operations were forced to shut down on March 18, 2020 due to COVID-19. Industrial lab use accounted for approximately 16% of the total hours of independent equipment use logged.

Infrastructure – Research Advancement Centres

As of March 31, 2020, there are 10 operational research labs in RAC (I and II), which include:

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

In RAC I, phase one of the design and assembly of the Quantum Explorations Space is complete. This space is used to give students and visitors access to real research-grade quantum systems for laboratory experiments and knowledge building. The space allows students in programs such as USEQIP and QCSYS to get detailed hands-on experience with real systems. In future, it will allow large numbers of industry experts and visitors to see real quantum devices in action.

Collaborations & 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 2019-2020, IQC faculty members collectively reported 108 active collaborations with 94 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 58.

- *Anyon System*
- *Honeywell (formerly called ComDev)*
- *National Research Council*
- *Canadian Security Intelligence Services*
- *Xiphos Systems*
- *University of Queensland*
- *University of California*
- *Swiss Federal institute of Technology*
- *InfoSec Global*
- *University of Ottawa*
- *Defense Research and Development Canada*
- *Canadian Securities Exchange*
- *Excelitas*
- *Perimeter Institute of Theoretical Physics*
- *M2lasers*
- *Mitacs*
- *Tsinghua University*
- *NIST Boulder Laboratories*
- *Cornell University*
- *University of Vienna*
- *Université de Montréal*
- *ID Quantique*
- *Centre for Quantum Technologies*
- *Université de Sherbrooke*
- *Massachusetts Institute of Technology*
- *University of Calgary*

In addition to maintaining and growing established relationships, IQC's researchers and stakeholder groups continuously seek new partnerships to support strategic research objectives. What follows are examples of some initiatives from 2019-2020:

- In the fall of 2019, staff facilitated half-day visits from Roche Pharmaceuticals leadership to explore potential areas of partnership. Faculty with related expertise in quantum sensing were invited to participate in meetings.

- Hosted the Korean Research Institute of Standards and Science (KRISS) to explore opportunities for collaboration in the area of quantum computation, materials, sensing and algorithms.

- IQC is working to develop industry programming and workshops aimed at raising the awareness of the benefit of quantum technologies and opportunities to collaborate with IQC experts. Community partners include Communitech Data Hub.

- NRCan is in process of determining its internal approach to quantum policy. In March 2020, IQC and the Office of the Chief Scientist met to discuss IQC participation as well as collaborative opportunities between researchers at the two organizations.

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:

- Continue to grow and attract the best talent to IQC's graduate program
- Field at least 200 applications to the University of Waterloo/IQC graduate studies program
- Expand connections made with undergraduate programs at Ontario and Canadian universities
- Continue to host timely, focused conferences, workshops, seminars and courses
- Host two major conferences
- Hold up to 10 workshops and seminars
- Jointly sponsor up to 10 workshops and conferences with national and international partner organizations

Attracting Talent – Postdoctoral Fellows

Postdoctoral fellowship positions provide young scientists opportunity for additional mentoring, to publish work and for research and teaching experience. In 2019-2020, IQC overachieved its goal of recruiting five new postdoctoral fellows by successfully recruiting a total of 29 – which represents a 15% increase from the previous year. Over the last fiscal year, IQC employed 65 Postdoctoral Fellows of which 20% 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 62.

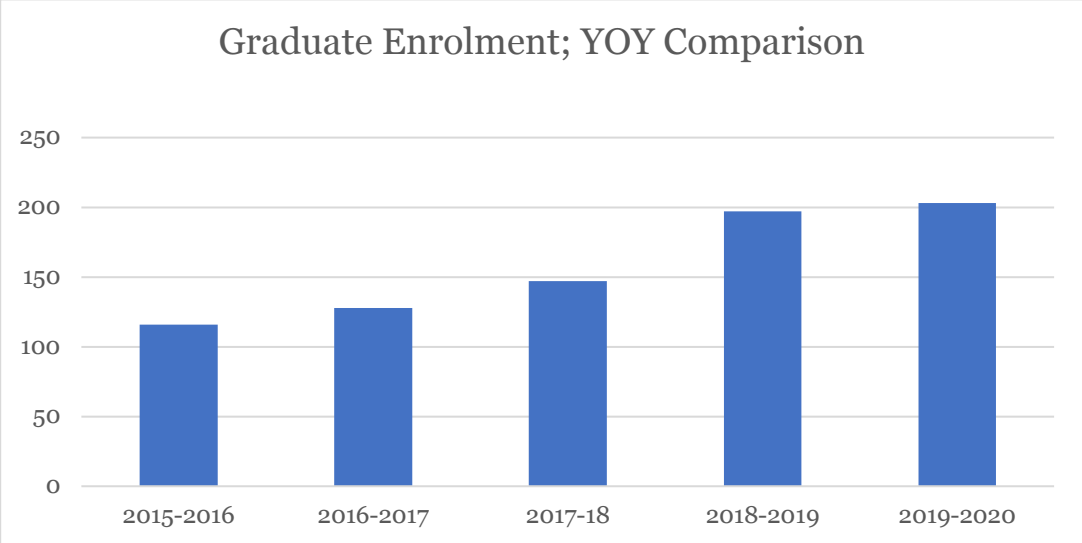
Canada	United States	International
Université de Sherbrooke	Massachusetts Institute of Technology	University College London
University of Toronto	Penn State University	University of Cambridge
University of Waterloo	University of Maryland	University of Sydney
Western University	University of West Virginia	Inria, Paris
		Tu Darmstadt

Since 2015, ten IQC PhD alumni have been awarded postdoctoral fellowships. These alumni represent a group of early researchers dedicated advancing to 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 faculty member, Joel Wallman was a postdoctoral fellow promoted to Research Assistant Professor.

Attracting Talent – Graduate Students

IQC welcomed 60 new graduate students this past year from 528 applications, bringing the total current number of Master's and PhD students to 203 (91 and 112, respectively). As depicted in the graph below, graduate enrolment at IQC continue to increase year over year.

It is noteworthy that in 2019-2020, the number of female applications into the quantum at the graduate level has doubled ($\bar{x}$=38 female applications per year to 80 applications). This increase is believed in part to be the result of Donna Strickland's success in winning the Nobel Physics Prize in 2018.

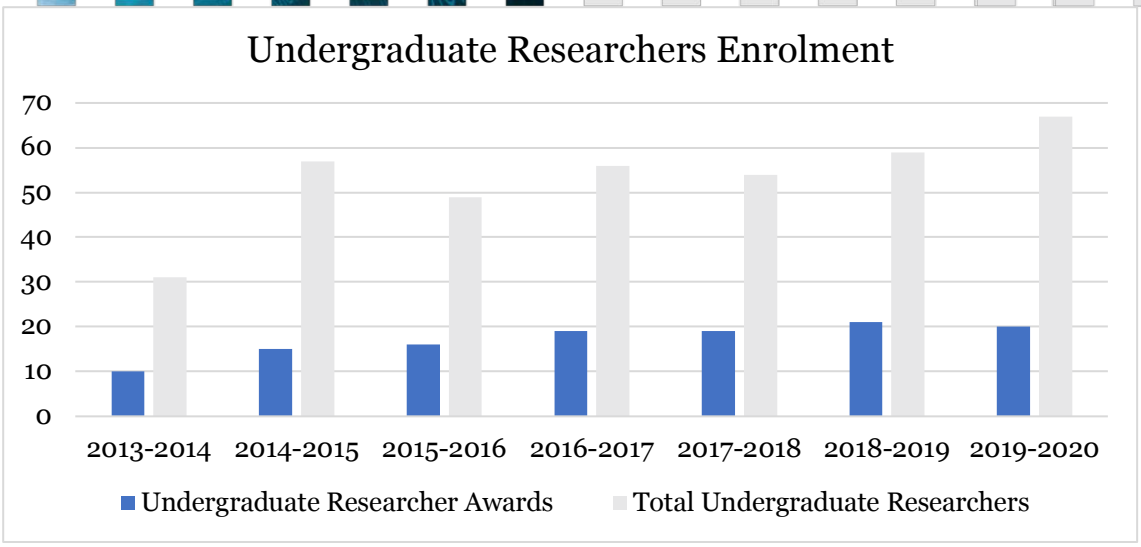


IQC is committed to equity, diversity and inclusion. 20% of IQC graduate students are women (20% Master's Students and 21% PhD Students). A full list of current graduate students currently studying at IQC can be found in Appendix F on page 63.

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.

The chart below reflects both the growth of USEQIP students who received Undergraduate Research Awards through the USEQIP program and undergraduate researchers who gain work opportunities at IQC through other channels, like co-operative employment positions. 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 the institution and return to IQC. Since the program's existence (2009), a total of 21 past USEQIP participants have returned to IQC to pursue graduate studies.

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 demonstrate their research excellence. In the last year, 165 IQC students were collectively granted 416 separate awards. Of the 165 IQC students, 30 were female who earned 85 (20%) of the 416 awards.

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

- *13 Mike & Ophelia Lazaridis Fellowship*
- *3 IQC Entrance Award*
- *43 International Doctoral Student Award*
- *27 International Masters Student Award*
- *1 IQC Achievement Award*
- *2 IQC David Johnston Award for Scientific Outreach*
- *7 NSERC Alexander Graham Bell Canada Graduate Scholarship - Doctoral*
- *3 NSERC Alexander Graham Bell Canada Graduate Scholarship - Masters*
- *5 NSERC Postgraduate Scholarship - Doctoral*
- *3 NSERC Vanier Canada Graduate Scholarship*
- *13 Ontario Graduate Scholarship*
- *31 President's Graduate Scholarship*
- *2 Provost Doctoral Entrance Award for Women wasn't a space between for and women*
- *1 Ontario Trillium Scholarship*
- *3 QEII-Graduate Scholarship in Science and Technology*

Expanding Connections

IQC has continued to participate in and sponsor undergraduate-level events hosted by the Canadian Association of Physicists (CAP), such as the Canadian Undergraduate Physics Conference (CUPC) and the Canadian Conference for Undergraduate Women in Physics (CCUWiP). We have also continued to present to undergraduate audiences around the country, including at University of Calgary in February of 2020.

In addition, members continue to give talks at Canadian universities throughout the year. Some examples from this year include:

- Michele Mosca presented at Wilfrid Laurier University on the challenges and opportunities of quantum computing and cybersecurity
- Na Young Kim spoke of artificial polariton band structures of two-dimensional honeycomb and kagome lattices at the Women in Physics Canada conference at McGill University
- Alex Cooper-Roy presented a talk at the University of Toronto on Quantum Simulation with Rydberg Atom Arrays

Conferences, Workshops, Seminars and Courses

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.

This past year, IQC was host to three major conferences, six workshops, 60 seminars and 21 colloquia, and jointly sponsored an additional 14 conferences and workshops held at partner organizations across the globe. Below are highlights of major conferences hosted and sponsored this year.

Major Conferences

In 2019-2020, IQC hosted three major conferences for attendees from around the world:

Ontario Association of Physics Teachers conference, May 3-4
In May, IQC hosted the Ontario Association of Physics Teachers (OAPT) conference. Teachers were able to attend workshops covering high-school and university physics teaching topics and pedagogy, with the theme of Entangling Learning.

Quantum Innovators: Science and Engineering, September 30-October 3
Held at IQC, the Quantum Innovators in Science and Engineering workshop occurred from September 30 to October 3. The workshop brought together the most promising young postdoctoral fellows in quantum physics and engineering, where they gave a talk on their research and collaborated with other participants as well as IQC members.

Quantum Innovators: Computer Science and Mathematics, October 21-24
IQC hosted its third annual Quantum Innovators in Computer Science and Mathematics from October 21 to 24. The workshop brought together young researchers working on theoretical aspects of quantum information and computation in computer science and mathematics. Guests were invited to a four-day conference aimed at exploring the frontiers of their field.

Workshops

Spin Canada, June 23-25

IQC sponsored the third annual Spin Canada workshop, held at the Fairmont Le Chateau Montebello in Quebec. It was co-organized by IQC's faculty member Jonathan Baugh in partnership with NRC's Sergei Studenikin with the main goal being to foster spin qubit research and attract and train highly qualified personnel for the emerging quantum technologies sector in Canada. The event brought together the Canadian community of scientists and engineers who perform research and development on spin-based quantum technologies, with 52 participants, 15 from IQC and/or University of Waterloo.

Waterloo-HKUST workshop, July 22-23

In July, IQC hosted the Waterloo-Hong Kong University of Science and Technology (HKUST) workshop on emerging quantum technologies in solid-state and atomic systems. This two-day workshop, organized by faculty member Na Young Kim, included eight other IQC affiliates who delivered presentations on their area of expertise, poster sessions and lab tours.

Quantum Key Distribution, August 19-23

In August, IQC hosted its biennial workshop, Quantum Key Distribution (QKD) summer school. The international QKD summer school is a five-day program focused on theoretical and experimental aspects of quantum communication with a focus on quantum cryptography and aims to provide a foundation in relevant approaches and techniques to enable graduate students and young postdoctoral fellows to perform their own independent research.

Schrödinger's Class, November 22-24

In November, IQC hosted its fifth annual high school teacher workshop, Schrödinger's Class. Here, teachers attend lectures and engage in hands-on activities focused on the integration of quantum technology into their current teaching curriculum. This workshop left teachers with the ability to teach quantum mechanics and discuss cutting-edge advances in the field, as well as take back lesson plans and other affordable, ready-to-go activities to be used in classrooms.

Quantum Illumination: From Theory to Practice, December 3-4

IQC hosted the workshop on Quantum Illumination: From Theory to Practice in December. Motivated by applications in defense, quantum communications and other areas, interest in Quantum Illumination has spread from academia to industry and government. The workshop brought together a wide range of participants from these various domains to discuss the state of the art in laboratory research, the range of possible applications, and paths toward those applications. This workshop was led by Christopher Wilson, a faculty member and Graduate Program Director at IQC, along with faculty members Michael Reimer and Jonathan Baugh. There were 56 attendees, representing the countries of Canada, the United States, Sweden, United Kingdom, Australia, Germany, China, Israel, India, and Italy. Regarding the participants' field of work, 46% were from academia, 29% from were government, and 25% were from industry.

IQC-IRIF workshop on Quantum Algorithms and Complexity, December 5

The one-day workshop is the third in a series that brings together researchers at Institut de Recherche en Informatique Fondamentale (IRIF), Université Paris-Diderot and IQC. It featured a full day of talks on recent progress in quantum algorithms and complexity theory, and related areas, made by members of the two institutions, with the idea to foster collaboration, led by faculty member Ashwin Nayak.

Finally, as a testament to IQC ability to pivot quickly and host timely conferences, the Institute held a half-day symposium when the APS Physics meeting was cancelled due to the rapidly escalating health concerns related to COVID-19. This symposium included presentations from the thirteen IQC researchers scheduled to talk at APS and a poster session. All talks were recorded and shared with APS to host.

Seminars & Colloquia

With events almost weekly, IQC's schedule of seminars and colloquia consistently keep the research community and their respective visitors engaged. This past year, IQC hosted 60 seminars and 21 colloquia. The increase in seminars comes from the newly launched student seminar series in FY2019-2020. The student seminars were introduced as a way to interconnect the 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 work on presentation skills. Appendix H, beginning on page 73 has a full list from this year.

Sponsored Conferences & Workshops

Each year, IQC commits to supporting external conferences and workshops to encourage opportunity for collaboration among a global network of researchers. This fiscal year, IQC sponsored 14 external events which are listed in the chart below:

Date	Conference	Location
April	Toronto Ultracold Atom Network Meeting	Institute for Quantum Computing
May-June	Theory Canada 14	University of British Columbia
June	Canadian Association of Physicists Congress	Simon Fraser University
June	Quantum Physics and Logic	Chapman University
June	Spin Canada	Fairmont Le Château Montebello
July	University of Waterloo-Hong Kong University of Science and Technology workshop	Institute for Quantum Computing
July	Women in Physics Canada	McGill University
August	Security Proofs of QKD workshop	University of Toronto
October	Quantum Internet Canada workshop	Sheraton Toronto Airport Hotel & Conference Centre
October	IQC-IRIF workshop on Quantum Algorithms and Complexity	Institute for Quantum Computing
October	Workshop on Quantum Foundations and Quantum Information	Centro Nacional Patagónico (CENPAT)
November	ETSI-IQC Quantum-Safe Cryptography workshop	Amazon Seattle
December	Quantum Illumination: From Theory to Practice	Institute for Quantum Computing
January	Canadian Conference for Undergraduate Women in Physics	University of Toronto

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:

- Promote Canada internationally as a place to conduct research in quantum technologies by participating in global quantum initiatives (including conferences, talks, seminars and other events);
- Being a catalyst for collaborations of quantum information scientists across Canada and around the world;
- Promoting collaborations through participation in national and international conferences;
- Producing internationally recognized, high-calibre publications co-authored by IQC researchers;
- Organizing 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 below and in the appendices.

Additional initiatives include those undertaken by the larger IQC community including:

AI Summit: Quantum Stream (San Francisco), September, 2019
John Donohue, Manager, Scientific Outreach and IQC PhD alumni presented to a full house at the AI Summit: Quantum Stream. Donohue shared background about IQC and recent research activities with 115 audience members. Additionally, IQC members continued conversations with the Federal and Provincial Trade Consulates in San Francisco on potential collaborations and future speaking opportunities as well as the Waterloo Regional Economic Development Team. IQC members also met with quantum companies with ties to Waterloo Region and Canada to foster collaboration.

QUANTUM: THE EXIBITION (Singapore), September 2019 – March 2020
After a successful tour to seven cities across Canada, the world's first-ever travelling exhibition on quantum information science and technology was rented to the Singapore Science Centre. Facilitated by partners at the Centre for Quantum Technologies (CQT) at the National University of Singapore, the exhibition was on display for over six months and received over 200,000 visitors.

IQC Quantum Day at Newlab (New York), July 10, 2019
IQC Faculty member, Michele Mosca, presented to an audience of CIOs on current and future issues related to quantum cryptography and security vital to the financial services industry. Additionally, IQC co-hosted a day-long summit with Newlab. Newlab membership includes 150+ member companies, partnerships with corporate entities, investors, and domain experts – all working together to scale frontier technologies. Raymond Laflamme and Joseph Emerson were among the speakers that discussed the Quantum Valley ecosystem clustered around the University of Waterloo and how IQC supports this research and start-up ecosystem.

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 58 provides a full list of all collaborative efforts this year (note: this list does not include co-authored publications.)

Tsinghua University
This past year, IQC initiated the renewal of the memoranda of understanding with Tsinghua University. IQC has seven official agreements to date with international organizations. These agreements facilitate collaborative research projects, joint research and the pursuit of common scientific interests. These official relationships offer scientists at both organizations a chance to visit, exchange ideas and collaborate with a new circle of researchers.

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 in discussions with the National Research Council team to participate in creating technologies enabling the implementation of next-generation, and next-after-next generation high speed telecommunication networks.

CryptoWorks21
IQC faculty member, Michele Mosca, founded CryptoWorks21 to prepare a new generation of researchers (graduate students and postdoctoral fellows) to create quantum-safe tools for the future. From its founding in 2012 until 2018 it was the NSERC CREATE Training Program in Building a Workforce for the Cryptographic Infrastructure of the 21st Century (CryptoWorks21) with partner institutions University of Calgary, Université de Montréal, and University of Waterloo. Since 2017, the program has been supported by the University of Waterloo and a donation from RBC.

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 130 conferences 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 66.

- *Cissy Patterson Lecture, College of William and Mary, USA*
- *SecTor2019, Toronto, ON, Canada*
- *Caltech High Energy Physics Seminar, California Institute of Technology, USA*
- *IDQ Winter School on Quantum Cybersecurity, Switzerland*
- *CROSSING Conference 2019, Germany*
- *X-ray and Neutron Phase Imaging with Gratings, Japan*
- *Quantum Optics and Laser Science (QOLS), Imperial College, UK*
- *Quantum Information Theory: Focus week on Foundations of quantum information, Autonomous University of Madrid, Spain*
- *Quantum Sensing, Spin Squeezing and related Technologies at SPIE Photonics West (OPTO), USA*
- *North American Conference on Trapped Ions (NACTI), University of Maryland, USA*
- *Dalhousie Mathematics Colloquium, Dalhousie University, Canada*
- *Quantum Tech conference, Boston, USA*
- *9th International Conference on Quantum Cryptography (QCrypt2019), Canada*
- *Bisynchronous Games, University of Edinburgh, Scotland, UK*
- *School of Mathematics and Physics Seminar, Queen's University, Canada*
- *International School on Quantum and Nano Computing Systems and Applications, Dayalbagh Educational Institute (DEI), India*
- *Canadian Semiconductor Science and Technology Conference, Canada*
- *Classical Algorithms for Quantum Mean Values, Instituto de Ciencias Matematicas (ICMAT), Spain*
- *NanoMRI 7, Weizmann Institute of Science, Israel*
- *US-Korea Conference 2019, Korean Federation of Science and Technology Societies, USA*
- *Women in Physics Canada Conference 2019, McGill University, Canada*

Produce internationally recognized, high-calibre publications co-authored by IQC researchers

Researchers at IQC collaborate with other researchers and scientists around the world to create scientific networks that produce the highest standard of research. Since 2002, 69% of all IQC papers are co-authored with researchers outside of Canada.

For a list of the 171 papers published this year, see Appendix B on page 48. A list of active collaborations by researcher can be found in Appendix D on page 58.

Organize conferences with multidisciplinary participants

The following three conferences were organized and presented by IQC this year:

Ontario Association of Physics Teachers conference, May 3-4
In May, IQC hosted the Ontario Association of Physics Teachers (OAPT) conference. Teachers were able to attend workshops covering high-school and university physics teaching topics and pedagogy, with the theme of Entangling Learning.

Quantum Innovators: Science and Engineering, September 30-October 3
Held at IQC, the Quantum Innovators in Science and Engineering workshop occurred from September 30 to October 3. The workshop brought together the most promising young postdoctoral fellows in quantum physics and engineering, where they gave a talk on their research and collaborated with other participants as well as IQC members.

Quantum Innovators: Computer Science and Mathematics, October 21-24
IQC hosted its third annual Quantum Innovators in Computer Science and Mathematics from October 21 to 24. The workshop brought together young researchers working on theoretical aspects of quantum information and computation in computer science and mathematics. Guests were invited to a four-day conference aimed at exploring the frontiers of their field.

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 FY2019-2020, IQC researchers collectively hosted 148 academic visits representing 141 unique scientific visitors from 100 unique organizations. Visiting organizations included:

Domestic	International
Dalhousie University	Centre national de la recherche scientifique
University of Calgary	Harvard University
University of Ottawa	Hong Kong University of Science and Technology
University of Toronto	Institute for Theoretical Physics ETH Zurich
University of Sherbrooke	Indian Institute of Technology Bombay
Western University	Massachusetts Institute of Technology
York University	University of California
	University of Cambridge
	University of Innsbruck

Nationally, IQC has strong relationships with other Canadian universities and organizations in quantum information science and technology. Additionally, IQC's international collaborations bring leading researchers to the Institute. In FY2019-2020, 84% of scientific visitors were from outside Canada.

A full list of academic and scientific visitors can be found in in Appendix I on page 75.

Short-term Visits & Tours

Hosting meetings and tours for industry, academia and government remains a key component of IQC's advancement activities. In 2019-2020, faculty and staff welcomed over 380 visitors to the Institute to tour facilities, meet with researchers and learn more about the Institute, its work, and potential opportunities for investment, partnerships and educational development. This past year, visitor numbers are slightly lower due to cancelations related to COVID-19.

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:

- Host USEQIP (undergraduate) and QCSYS (high school) summer schools
- Host the fifth annual high school teacher's workshop
- Host outreach events including public lectures and increase the knowledge of event participants on quantum information and IQC
- Present programming to promote science to women and girls
- Host QUANTUM: The Exhibition on an international stage
- Continue to leverage the quantum pop-up exhibit at select events
- Establish relationships with key strategic partners to further share IQC's research discoveries
- Continue to share IQC's research through publications, new stories/press releases, web and social media platforms
- Continue to drive new and unique visitors to IQC's website

USEQIP

IQC hosted its 10th annual Undergraduate School for Experimental Quantum Information Processing (USEQIP) from May 27 to June 7. This program 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.

This year, 16 female and 12 male students were selected out of 274 applications. This reflects an approximately 1:10 acceptance rate to the program, and an 63% increase in applications compared to 5 years ago. Participants came from across Canada, as well as the United States, India, Brazil, Nepal, Bosnia, Argentina, Mexico and Australia.

In a survey of the students following the summer school, 100% of the students reported they would actively encourage others to apply to USEQIP. 100% of respondents agreed or strongly agreed with the statement, "The program gave me the tools I need to begin investigating the quantum information field."

> *"It is an experience like none other. So amazingly planned and executed. We get to meet some of the greatest minds in the world and look at all the research that's going on. This experience increased my love for Quantum and excitement for a life in research many folds. Anyone who wants to see what actual world-class research looks like and what an amazing work environment feels like should definitely attend this school!"*

"USEQIP 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. I came out of the program with a much better sense of the current state of quantum computing and the current work being done in the field. IQC itself also seems to have set up a wonderful environment for academia. I can't pin it down exactly - it might be the back-to-back lectures with IQC faculty, or getting to play with a 2-qubit quantum computer, or the comfy couches - but it feels like everyone has become substantially more ambitious with respect to their academic goals."

QCSYS

IQC hosted its 11th annual Quantum Cryptography School for Young Students (QCSYS) summer school from August 9 to 16. IQC invited 44 participants to Waterloo to learn about quantum cryptography – a cutting-edge field that utilizes the laws of quantum mechanics to develop unbreakable encryption that protects communication. IQC received 309 applications from high school students around the world, generating more applications than ever before. This translates to one student being accepted for every seven applications. Of the 44 students accepted, 22 were female and 22 were male. Collectively, they represented Canada, the United States, Brazil, England, Tunisia, China, Switzerland, Kuwait, and Trinidad and Tobago.

In a survey of the students following the summer school, 100% of respondents rated the program as excellent (86%) or good (14%). 97% of respondents strongly agreed with the statement, "QCSYS exposed me to ideas not available in my high school classes."

"It's a wonderful one-week opportunity to strengthen one's skills in math and physics and it's a great way to expose high school students to the intricate field that is quantum mechanics. It's also an amazing way to meet like-minded exceptional students like you and create friendships that could last beyond high school."

Schrödinger's Class

IQC hosted its fifth annual high school teacher workshop, Schrödinger's Class, from November 22 – 24. Forty invitations were sent after receiving 112 applications, generating the most applications compared to previous years. Out of 39 acceptances, 18 male and 21 female teachers travelled to Waterloo to attend lectures and engage in hands-on activities focused on the integration of quantum technology into their current teaching curriculum. This workshop left teachers with the ability to teach quantum mechanics and discuss cutting-edge advances in the field, as well as take back lesson plans and other affordable, ready-to-go activities to be used in classrooms.

In a survey of the teachers following the workshop, 100% of respondents rated the program as excellent (94%) or good (6%). 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 22 teachers.

"The material presented helped me understand quantum mechanics in a way I didn't before. The activities presented are something I can and will do with my students. The opportunity to meet with other teachers and discuss how they do things was also very valuable."

"The opportunity to have so much great instruction on modern physics from experts who are also excellent teachers is unbelievable. There is no other way to achieve this level of comfort with and excitement for this content. Additionally, the opportunity to collaborate with other teachers is invaluable."

Public Lectures

This year, IQC continued its series of public lectures called Entangled: The Series. On May 7, IQC Scientific Outreach Manager John Donohue presented Quantum + Pop Culture, a lecture on quantum's connections to popular media and depictions of new technologies, at the Apollo Cinema, a small local business, with over 100 guests in attendance. The second Entangled lecture of the year was Quantum + Security, brought over 40 members of the community into the IQC space to hear from Michele Mosca, an IQC faculty member who discussed quantum's connection to information security.

Beyond lectures, IQC has engaged the local community with events such as Quantum + Trivia, a quantum-themed trivia night hosted in partnership with the Round Table Board Game Café, another small local business and by opening Quantum: The Pop-Up Exhibition at the City of Waterloo's LUMEN light festival.

Outside of Kitchener-Waterloo, IQC has partnered with partners such as The Royal Canadian Institute for Science (RCI Science), the TelusSpark science center, and the Newlab business incubator to present Quantum + Pop Culture to public audiences in Toronto, Calgary, and New York City. The talk presented at RCI alone had an audience of 190 people, and generated great survey results, including approximately 92% of participants feeling that they left better informed about quantum.

On March 27, 2020, IQC partnered with Exploring by the Seat of Your Pants to present a free online lecture aimed at middle-school and high-school students on the science of light while schools were closed due to COVID-19.

High School Visits

IQC launched a pilot program in January 2020, called the Unentangled series. It includes travelling workshops where IQC visited schools in the surrounding regions to deliver quantum cryptography workshops to science classes. These workshops were brought to eight schools in Kitchener, Waterloo, Woodstock, Guelph, Stratford, and Brantford, reaching over 350 students, mostly in Grade 11 and 12.

Additionally, IQC hosts school visits during April and December each year as part of Physics Lab Days program at the University of Waterloo. John Donohue (Manager, Scientific Outreach and PhD Alumni), runs workshops for visiting Grade 11 and 12 students. In total, 28 classes from the region visited the Quantum-Nano Centre, bringing in 699 students to learn about quantum physics and cryptography.

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 colloquia, like the Women in Science Meet and Greet, where IQC invited Nicole Yunger Halpern from the Harvard-Smithsonian Institute for Theoretical Atomic, Molecular and Optical Physics in April.

Through partnerships with groups such as the Canadian Association of Girls in Science (CAGIS), IQC has been able to reach groups traditionally underrepresented in STEM fields. In September, IQC hosted an event in collaboration with CAGIS, bringing 38 girls between the ages of 8-14 to the Quantum-Nano Centre for scientific workshops. The younger group worked on a Mars-inspired aerodynamics activity, while the older group used quantum principles and lasers to estimate the width of their hair. The event was covered by CTV and featured on their "In Your Backyard" series. IQC was responsible for the workshop content and event space, while CAGIS promoted the event to their network.

In October, IQC hosted 107 middle- and high-school students for a full day of science-based activities centred around space to kick-off the NASA SpaceApps Hackathon. IQC graduate students presented on black holes and quantum experiments in space. IQC organized and moderated a panel discussion on Women in STEM to close the event, with topics spanning careers in academia, what being a good ally means and why the fields of science and math need more women in them. IQC was responsible for the event space, panel, and quantum session.

In collaboration with the University of Waterloo undergraduate registrar's office, IQC planned a Women in STEM panel to showcases the wide-ranging journeys that women in the fields of math, science and engineering have taken after earning an undergraduate degree from UWaterloo. While the event was postponed due to COVID-19, IQC will be looking to host similar panels with the university in the next fiscal year.

Additionally, IQC hosted workshop sessions during events promoting science to young women organized through the larger university campus, including the Centre for Education in Mathematics and Computing's (CEMC) May 13 Workshop in Computer Science for Young Women (36 Grade 9 and 10 students) and the Department of Physics & Astronomy's PhysiX: Girls Matter event on November 30 (40 participants in Grade 7 and 8).

QUANTUM: The Exhibition

After a successful tour to seven cities across Canada, the world's first-ever travelling exhibition on quantum information science and technology was rented to the Singapore Science Centre. Facilitated by partners at the Centre for Quantum Technologies (CQT) at the National University of Singapore, the exhibition was on display for over six months and received over 200,000 visitors.

To date, the exhibition has received over 900,000 visitors in total.

QUANTUM: The Pop-Up Exhibit

QUANTUM: The Pop-Up Exhibit was featured as part of the Lumen festival of light hosted by the City of Waterloo on September 27 2019. The festival saw more than 15,000 attendees from the region, and The Pop-Up Exhibit gave them the opportunity to engage with quantum physics and quantum scientists.

Additionally, the Exhibit was also featured as part of QuickenTechCon at the TCF Center in Detroit, Michigan on October 17 2019. QuickenTechCon, hosted by Quicken Loans, brought together approximately 3000 members of their company, and the Pop-Up Exhibit along with a keynote address from IQC affiliate Prof. Shohini Ghose exposed this audience to new quantum concepts.

In March 2020, QUANTUM: The Pop-Up Exhibit was featured at the Canadian Security Intelligence Services (CSIS) headquarters, accessible to all on-site employees. It was used, along with roundtables and talks by IQC faculty, to increase awareness of quantum information science and technology in the security sector. This was the first time CSIS had hosted an external exhibit like IQC's Pop-Up Exhibit.

Strategic Outreach Partnerships

As mentioned earlier, IQC has continued partnerships with local businesses and with larger groups such as RCI Science and TelusSpark to broaden our voice in the community and beyond. To reach broader audiences online, we have partnered with Exploring by the Seat of Your Pants. To increase our reach to underrepresented groups, we have partnered multiple times with the Canadian Association for Girls in Science (CAGIS). We have presented workshops and booths at events such as Ingenium's Cool Science Saturday and NSERC's Canada-Wide Science Fair.

IQC also partnered with industry groups, including Roche Pharmaceuticals and Newlab in New York, to arrange educational quantum events for their employees, leadership, and community.

As mentioned in the QUANTUM: The Pop-Up section, IQC was also invited to present an Expert Briefing at a Canadian the Canadian Security Intelligence Services (CSIS). The Expert Briefing provided a general overview of quantum technologies (including quantum sensing, communications and computing), recent activities at IQC and how they support Canada's emerging quantum economy. The briefing was presented in person and was broadcast across government departments. Demand for the briefing exceeded spots available for the in-person session, leading to a second presentation for Global Affairs Canada later that same day. Additionally, IQC participated in closed-door discussions with intelligence personnel and invited guests.

Communications

The Communications team at IQC ensures researchers and their work are recognized worldwide through news stories, media release, 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 numerous research results reported on each year, IQC's communications team strives to promote the Institute's work to the mainstream media. This year, approximately 446 media mentions of IQC were recorded which translates to a reach of 558,820,000 impressions (the number of times that a post has appeared in a feed).

Media outlets including the National Post, CTV, Globe and Mail, The Independent, Maclean's, TechRadar, Gizmodo, The Hill, Global News, ScienceDaily, Toronto Star, the National Observer, and many more have all mentioned or cited IQC or IQC researchers in the last year, demonstrating IQC's global presence in this industry.

Print Publications

2019-2020 has been a year of change for IQC's print publications:

The Annual Report has become the Impact Report to better emphasize the impact of IQC research on the field of quantum information science and technology, and to highlight areas of current and potential societal and economic impact. The IQC Impact Report will be accompanied by an online version in English and, for the first time in French. Both sites will be launched in FY2020-2021. In addition, stories will be shared broadly through an extensive social media campaign.

The electronic version of the report will allow IQC to share the stories of its researchers and the current and potential impact of quantum information research as broadly as possible, while also increasing the measurability of this effort. COVID-19 has delayed the launch of the Impact Report beyond the expected reporting year.

This year also provided an opportunity for IQC to redesign NewBit, which has traditionally been a print publication originally written for an internal audience. Much loved by visitors and our larger community, NewBit now serves an externally facing audience. Moving forward, NewBit (under a new moniker) will live primarily online as a venue for in-depth explorations of the research performed by IQC researchers, and the potential for this research to drive new discoveries and technologies. This content will be highly shareable and search engine optimized to ensure a broad spread of awareness about quantum information science and technology and IQC's contributions to those areas. This content will also be printed annually as a magazine that will be made available to the public and distributed at relevant events.

Website

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

The traffic to the IQC website has increased over the previous year – there has been 119,641 unique visitors in FY2019-2020 compared to 111,135 in FY2018-2019. Approximately, 70% of web traffic is from outside Canada. The average pages per session was two (average page per session shows the number of pages the user engages with beyond their landing page).

At the time of writing this report, organic search was responsible for 62% of the traffic to the IQC website, followed by social media (21%). The click-through rates on Facebook and Twitter posts linking to the IQC website increased dramatically (67% and 43%, respectively).

To maximize audiences' online experience and SEO rankings, IQC launched an in-depth website content audit. Consequently, the communication team has updated and optimized the organization, presentation and content of much of the website. This process will continue into the next fiscal year.

Social Media

Throughout last year IQC enjoyed steady growth across all its social media platforms. Below are some highlights of social platform growth from April 1, 2019 to March 31, 2020.

	New Followers	Total Current Followers	Increase
YouTube	3,074	17,800	21%
Facebook	378	5,300	8%
Twitter	1,352	13,700	11%
Instagram	249	900	38%

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

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:

- Support building of a new Quantum Industry
- Promote 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

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 2020, IQC researchers collectively held over 47 patents and 30 licenses including three new patents granted in 2019-2020. Currently, IQC faculty have 94 patent applications pending approval.

Start-up companies are being established that bring quantum technologies out of the labs and into the marketplace. To date, the below fourteen spinoffs companies have emerged from IQC research.

IQC quantum spin-off companies:

- EvolutionQ
- High Q Technologies LP
- Neutron Optics
- Quantum Benchmark Inc.
- QuantumLaf Inc.
- QuSpin Technologies Inc.
- Universal Quantum Devices
- Single Quantum Systems
- Aurora Quantum Technologies (formerly known as QSpiceLabs)
- QEYnet
- SoftwareQ Inc
- Everettian
- SpinQ
- Q-Block Computing Inc.

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

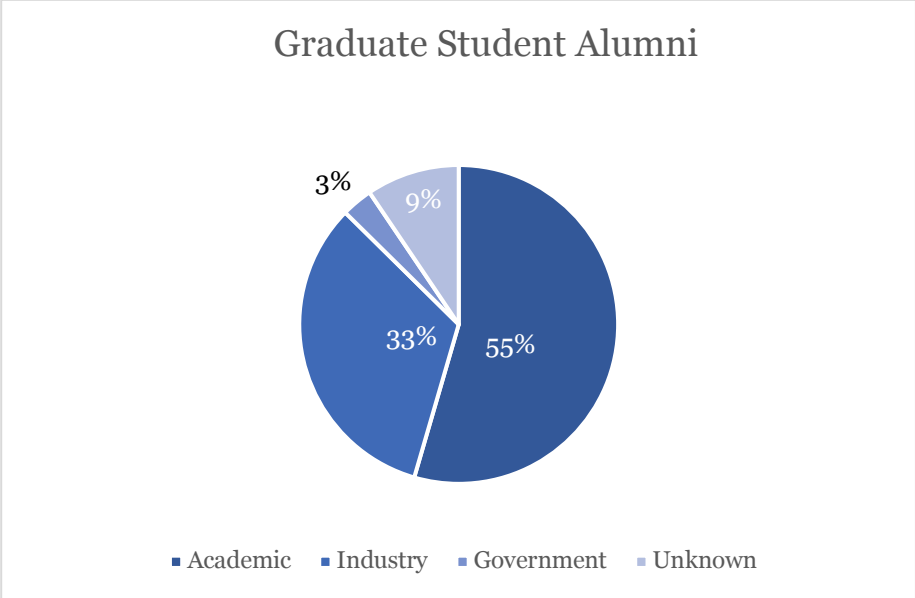
Additionally, IQC researchers are supporting local companies through their shared expertise, collaboration and mentorship. IQC is unique in having the breadth of knowledge to develop innovative ideas that advance quantum technology and the infrastructure required to turn those ideas into reality quickly and efficiently. Connecting IQC advances to applications is a valued and essential element of the IQC culture.

IQC Alumni: Training the Quantum Workforce

IQC alumni leave campus and become global citizens who impact academic, industry and government sectors. They inspire future quantum innovators with their passion, purpose and intellect. IQC alumni spur quantum advancements in a broad range of fields including banking, communications, and technology. IQC alumni include both graduate student and postdoctoral fellow alumni.

Graduate Students

This year, IQC proudly reports granting degrees to 38 Master's students and 16 PhD students, bringing the total number of student alumni to 269 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, 2020, 33 IQC graduates are working in the Quantum Information (QI) field in Canada, of which 6 are women. An additional 16 are employed as postdoctoral fellows at Canadian Universities.



Student Alumni Profiles

Dariusz Lasecki

Dariusz Lasecki had his first experience with IQC when he attended the Quantum Cryptography School for Young Students (QCSYS) in 2013. The program sparked Lasecki's interest in quantum and seeing the state-of-the-art experimental labs inspired him to then conduct research at the institute.

Lasecki returned to IQC as a recipient of an Undergraduate Research Award (URA) and an attendee of the Undergraduate School on Experimental Quantum Information Processing (USEQIP) in 2016. USEQIP enhanced his understanding of theory by deepening his knowledge of experimental techniques, such as using optical devices to implement the BB84 quantum key distribution scheme. Lasecki's theoretical research as a URA looked at methods of communication between two parties using quantum data.

Lasecki returned to IQC again the next year to complete his Master's. "The programs at IQC have given me a much better understanding of how scientific research is conducted," said Lasecki. This understanding has helped him to succeed in industry, where he currently works as an Associate Software Engineer at TomTom.

Aimee Gunther

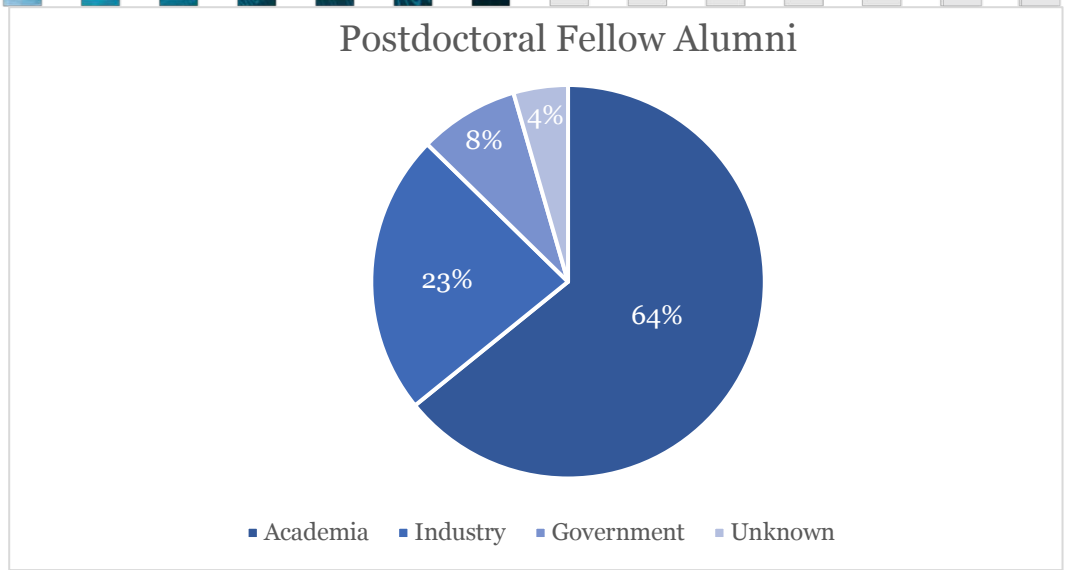
There's more to the field of science than just experimenting and analyzing data for IQC alumna Aimee Gunther. For her, stepping out of the lab is an important part of becoming a well-rounded scholar. During her Master's and PhD at IQC, Gunther specialized in the development and manipulation of quantum photon pair sources. Beyond the lab, she developed skills in higher education and science policy and communication.

"Even though I've spent a whole decade looking at experimental quantum optics and energy—an incredibly niche field of quantum research—I believe there are a lot of other fascinating problems out there," said Gunther before she had finished her PhD.

Now a Quantum Science Advisor at Defence Research and Development Canada, Gunther credits her love for learning and transferable skillset to her time studying at IQC: "I am a stronger researcher because of the opportunities and experiences I've had."

Postdoctoral Fellows

In contrast to the stories of postdocs challenges to find employment after leaving academia, postdoctoral fellow alumni are regarded as role models, visionaries, and leaders of the quantum industry, by their peers. Our alumni leave campus and become global citizens who impact academic, industry and government sectors. Below a is representation of where IQC postdocs have gone as of March 31, 2020:



Postdoc Profiles:

Anne Broadbent

Technological advances will see the need for a deeper theoretical understanding of quantum information at all levels, predicts Anne Broadbent, Assistant Professor and University Research Chair in Quantum Information Processing at the University of Ottawa. Broadbent was a postdoctoral fellow at IQC until 2013. She held an NSERC postdoctoral fellowship and was also a CIFAR Global Scholar. Her research focused on quantum cryptography and developing methods for delegating private quantum computations and quantum one-time programs.

Broadbent acknowledges the value of exposure to a broad range of research topics and experience in training students during her time at IQC. Now leading her own research group at the University of Ottawa, Broadbent continues to push the limits of our understanding of how quantum information provides advantages in all aspects of cryptography. She has also further developed techniques for outsourcing quantum computations in terms of quantum homomorphic encryption, as well as verifying remote quantum computations.

Scott Aaronson

After completing a postdoctoral fellowship at IQC in 2007, Scott Aaronson accepted the position of Associate Professor of Electrical Engineering and Computer Science at the Massachusetts Institute for Technology in Cambridge, Massachusetts. He moved to the University of Texas at Austin as David J. Bruton Jr. Centennial Professor of Computer Science and as the founding director of UT Austin's new quantum computing center.

His research interests include the capabilities and limits of quantum computers and computational complexity theory. His recently published book Quantum Computing since Democritus provides insight and perspectives into “the deepest ideas of math, computer science and physics.” Aaronson is also known for his blog Shtetl-Optimized about quantum computing and quantum information science. Aaronson credits his time at IQC for “bringing him out of his shell” and also where he learned to drive.

Urbasi Sinha

Former IQC postdoctoral fellow Urbasi Sinha's research focused mainly on quantum optics-based tools used to perform fundamental tests of quantum mechanics. During her time at IQC, Sinha developed a holistic approach towards her research that she finds useful in her current role as Associate Professor at the Raman Research Institute in India. "At IQC I learned how to accept success and failure with equal gusto and carry on enthusiastically with results both big and small," says Sinha.

Currently, a major aspect of her research involves manufacturing and employing single photons and entangled photons produced by spontaneous parametric down conversion towards experiments in quantum information and computing. One of her experimental projects explores the use of multiple slits as possible qudits and investigating higher dimensional quantum correlations through studies of entanglement-based phenomena.

Attracting Companies to the Quantum Valley

The IQC and the CFREF-TQT programs have been instrumental in attracting Canadian and international based quantum companies to grow their operations to Waterloo Region including 1QBit (headquartered in Vancouver) Ambature (based out of the US) and Anyon Systems (based out of Dorval). These companies are attracting highly qualified researchers to the region and will further strengthen collaborations with Waterloo's Quantum Valley community. These companies have expanded to Waterloo Region to benefit from the ease to recruit highly qualified quantum talent, access of the Quantum-Nano Fabrication and Characterization facility for testing and prototyping; and the strength of the localized quantum community.

IQC and the CFREF-TQT have also developed a first-of-its-kind collaboration between academia and industry to facilitate research building and partnerships. Launched in fall 2019, the program focused on events to link academia and industry including focused workshops, showcases, embedded researchers, quantum researchers and access to quantum talent.

APPENDICES

A. Risk Assessment & Mitigation

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

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
COVID pandemic extends into fiscal 2021-2022	High	Medium	8	If shelter-in-place remains long-term, labs will remain inaccessible and events will be postponed or cancelled thereby impeding in-person collaboration and research.	Identify and implement new approaches to virtual collaboration and events. Retool and install equipment to further enable remote access to labs and research facilities.
Search for new Executive Director	Medium	Medium	5	Employment search will extend over next year.	Continue hiring process with exceptionally strong candidates. Maintain search for other eligible candidates until offer accepted. Promote and support Interim Director in the running of IQC.
Transformational technologies may render current research less relevant	High	Low	6	If IQC research is rendered less relevant, HQP and data seekers will go elsewhere.	Ensure a wide breadth of research to investigate (this would differentiate IQC from its competitors). Continue applications for research funds to support leading-edge equipment.
IQC may not be able to recruit enough HQPs	High	Low	6	Many international HQPs come from potentially politically unstable countries (top three: Iran, China, India).	Promote IQC sufficiently. Ensure excellent research. Diversify markets/ countries from which students are recruited.
Operating constraints limit IQC's efforts to brand itself	High	Low	6	Operating constraints include limited resources (including staff), degree of flexibility.	Recruit the right people/talents/skills. Develop and deliver a branding project plan. Foster close working relationships with appropriate units

					within the university.
Federal Government funding renewal declined or reduced significantly	High	Medium	8	Government quantum fatigue and unaligned priorities may result in funds being invested elsewhere. This would have a devastating impact on IQC's ability to operate and position Canada as a quantum leader on the world stage.	Underscore relevance of IQC in addition to performance. Increase focus on methods of bringing in funds from private investors. Continue to build strong relationships with all levels of government.

B. Publications

April 1, 2019-March 31, 2020

1. Ahmadzadegan, A., Lalegani, F., Kempf, A., Mann, R. B. (2019). Probing geometric information using the Unruh effect in the vacuum. Physical Review D, 100 (8).
2. Al Alaeian, H., Chang, C., Wai, S., Moghaddam, M. V., Wilson, C. M., Solano, E., Rico, E. (2019). Creating lattice gauge potentials in circuit QED: The bosonic Creutz ladder. Physical Review A. 99 (5).
3. Alhambra, A. M., Styliaris, G., Rodriguez-Briones, N.A., Sikora, J., Martin-Marinez, E. (2019). Fundamental Limitations to Local Energy Extraction in Quantum Systems. Physical Review Letters. 123 (19).
4. Amy, M., Mosca, M. (2019). T-Count Optimization and Reed-Muller Codes. IEEE Transactions on Information Technology. 65 (8).
5. Anshu, A., Berta, M., Jain, R., Tomamichel, M. (2019). Second-Order Characterizations via Partial Smoothing. 2019 IEEE International Symposium on Information Theory (ISIT).
6. Anshu, A., Boddu, N. G., Touchette, D. (2019). Quantum Log-Approximate-Rank Conjecture is also False. 2019 IEEE 60th Annual Symposium on Foundations of Computer Science (FOCS 2019).
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Austin Woolverton
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Ruoxuan Xu
Fangzhou Yin

G. Invited Talks & Conference Participation

Faculty Member	Title/Subject	Institution/Conference
Michal Bajscy	Quantum Innovators Workshop	IQC, Waterloo, ON, Canada, Sept 30 - Oct 3, 2019
	Polarization dichroic mirrors for quantum optics with atomic ensembles	Quantum Sensing, Spin Squeezing and related Technologies at SPIE Photonics West (OPTO), San Francisco, CA, USA, Feb 1, 2020
Jonathan Baugh	Nanostructure devices for quantum information	Guelph-Waterloo Centre for Graduate Work in Chemistry, Guelph, ON, Canada, October, 2019
	A network architecture for topological quantum computing in silicon	European Solid-State Circuits, Krakow, Poland, September, 2019
	A pathway for quantum computing in silicon	Canadian Semiconductor Science and Technology Conference, Saskatoon, SK, Canada, July, 2019
	A pathway for quantum computing in silicon	McGill Physics seminar, Montreal, QC, Canada, April, 2019
	Spin Canada (Main Organizer)	Montebello, QC, Canada, June, 2019
	Quantum Illumination: From Theory to Practice	IQC, Waterloo, ON, Canada, December, 2019
Raffi Budakian	NanoMRI 7	Weizmann Institute of Science, (virtual conference presentation online), March 29 - April 2, 2020
Kyung Soo Choi	Many-body QED with atoms and photons: A new platform for quantum optics	Okinawa Institute of Science and Technology, Okinawa, Japan, June, 2019
	Many-body QED with atoms and photons: A new platform for quantum optics	IBS symposium on atomic quantum information science, Seoul, South Korea, June, 2019
	Many-body QED with atoms and photons: A new platform for quantum optics	Frontiers in Optics/Division of Laser Science 2019, Optical Society of America and American Physical Society, Washington, DC, September, 2019
Richard Cleve	What can be done with extreme entanglement?	DPG (German Physical Society) Fall Meeting on Quantum Science and Information Technologies, Freiburg, Germany, September, 2019
	Embezzlement and nonlocal games	Banff International Research Station meeting on The Many Faceted Connes Embedding Problem, Banff, AB, Canada, July, 2019
David Gosset	Quantum advantage with shallow and noisy circuits	Dalhousie Mathematics Colloquium, Dalhousie University, NS, Canada, April 11, 2019
	Quantum advantage with shallow and noisy circuits	Xanadu AI, Toronto, ON, Canada, May 29, 2019
	Quantum advantage with shallow and noisy quantum circuits	TQC invited talk, College park, Maryland, USA, June 5, 2019
	Simulation of quantum circuits by low-rank stabilizer decompositions	NISQ invited talk, College park, Maryland, USA, June 7, 2019
	Entanglement subvolume law for 2D frustration free spin systems	QMATH 14, Aarhus University, Denmark, August 14, 2019
	Classical algorithms for quantum mean values	Instituto de Ciencias Matematicas (ICMAT), Madrid, Spain, October 10, 2019
	Approximation algorithms for quantum many-body problems	Workshop on Noncommutative Analysis, Computational Complexity, and Quantum Information, Harvard University Center for Mathematical Sciences and Applications, Cambridge, USA, October 18, 2019
	Classical algorithms for quantum mean values	QIP 2020, Shenzhen, China, Jan 6, 2020
	Classical algorithms for quantum mean values	Simons Center workshop on quantum algorithms, Berkeley, CA, USA, February 26, 2020

Faculty Member	Title/Subject	Institution/Conference
Thomas Jennewein	Towards global Quantum Communication using Satellites	OSA, Rome, Italy, April 4-6, 2019
	Panelist speaker for the theme "Academia, Industry and Government"	OSA, Melbourne, Florida, USA, May 16, 2019
	Towards global quantum communications based on ground to space quantum links	Photonics North, Quebec, Canada, May 21, 2019
	Quantum Communication with Satellites	University of Waterloo, Waterloo, Canada, June 21, 2019
	Global Quantum Communication Networks: Ground to Space Quantum Links	AFRL, Rome, NY, USA, July 9-11, 2019
	Quantum communication over free space and towards satellites	University of Waterloo, Waterloo, Canada, July 22-23, 2019
	Novel avenues for robust free-space quantum communications	National University of Singapore, Singapore, August 29, 2019
	Novel avenues for robust free-space quantum communications	QOLS, Imperial College London, London, UK, September 25, 2019
	Novel techniques for ground to space quantum channels	QTX-3, Newport, UK, September 27, 2019
	Attended only	Quantum Internet Canada workshop, Toronto, Canada, October 1-2, 2019
	Novel avenues for robust free-space quantum communications	University of Chicago, Chicago, USA, October 24-25, 2019
	Towards a global quantum internet using satellite-based quantum communication receiver	ICSCC, Okinawa, Japan, October 28-31, 2019
	Towards a quantum internet, and its applications	Brookhaven, NY, USA, November 19, 2019
	The quantum internet, and its applications	IQC, Waterloo, Canada, December 3-4, 2019
Na Young Kim	Quantum Computing in US and Canada	Canada-Korea Conference on Science and Technology, The Association of Korean-Canadian Scientists and Engineers, Banff, AB, Canada, June 16, 2019
	Bloch Exciton-Polariton in Two-Dimensional Honeycomb and Kagome Lattice	The Women in Physics Canada Conference 2019, McGill University, Montreal, QC, Canada, June 27, 2019
	Bloch Exciton-Polariton Quantum Simulation	Waterloo-HKUST workshop on Emerging Quantum Technologies in Solid-state and atomic systems, IQC, Waterloo, ON, Canada, July 22, 2019
	Engineerable solid-state systems: quantum wells and carbon nanotubes	Quantum Materials 2019, University of Waterloo, Waterloo, ON, Canada, July 26, 2019
	Low-frequency Noise properties of CMOS Transistors at Cryogenic Temperatures	US-Korea Conference 2019: Smark Science, Engineering and Health for Livable Communities, Korean Federation of Science and Technoloogy Societies, Chicago, IL, USA, August 15, 2019
	Quantum Past, Present, and Future: Quantum Innovation Laboratory	US-Korea Conference 2019: Smark Science, Engineering and Health for Livable Communities, Korean Federation of Science and Technoloogy Societies, Chicago, IL, USA, August 17, 2019
	Characterization of hexagonal Boron Nitride Langmuir-Blodgett Films	19th Canadian Semiconductor Science and Technology Conference/Alan J. Malcolm, University of Saskatchewan, SK, Canada, July 19, 2019
	Embezzlement-based nonlocal game (Bell inequality) that cannot be won (violated) optimally with finite amount of entanglement (i.e., proving the set of quantum correlations is not	Banff International Research Station, Calgary, AB, Canada, April 21-26, 2019

Faculty Member	Title/Subject	Institution/Conference
	closed using embezzlement), Quantum Walks and Information Tasks	
	Embezzlement-based non-local game that cannot be played optimally with finite amount of entanglement	CIFAR Quantum Information Processing program meeting, Montreal, QC, Canada, May 14-17, 2019
	Embezzlement of entanglement	Colloquium, Perimeter Institute, Waterloo, ON, Canada, May 28, 2019
Debbie Leung	The curious capacities of quantum channels	Quantum Information and Quantum Computation Initiative (QICi) seminar, University of Hong Kong, China, August 9, 2019
	The curious capacities of quantum channels	Young Researcher Forum on Quantum Information Science, National Tsing Hua University, Taiwan, China, August 14-16, 2019
	Embezzlement and Applications	19th Asian Quantum Information Science Conference (AQIS), KIAS, Seoul, Korea, August 19-23, 2019
	Simple proof of non-closure of quantum correlations using embezzlement	Analytical and combinatorial aspects of quantum information theory, International Centre for Mathematical Sciences (ICMS), University of Edinburgh, UK, September 9-13, 2019
	Embezzlement and Applications	Quantum Information Theory, Focus week on Foundations of quantum information, ICMAT, Autonomous University of Madrid, Spain, September 23–27, 2019
	Incompressibility of classical distributions	CQuIC Seminar, University of New Mexico, NM, USA, November 14, 2019
	Incompressibility of classical distributions	Tutte Colloquium, University of Waterloo, ON, Canada, November 29, 2019
Adrian Lupascu	Investigation of connectivity in quantum annealers	University of Southern California, Los Angeles, CA, USA, February 25, 2020
	Design of High-Order and Long-Range Interactions for Quantum Annealers	Physics Colloquium, University of California at Merced, Los Angeles, CA, USA, February 28, 2020
Norbert Lutkenhaus	Entanglement routing and management in a large quantum network	Workshop on Quantum Network Science, University of Arizona, Tucson, Arizona, USA, May 13-14, 2019
	Quantum Communication with Coherent States of Light	Quantum 2019, Cavallerizza Reale, University of Torino, Turin, Italy, May 26 - June 1, 2019
	Quantum Communication with Coherent States of Light	CEWQO 2019, Paderborn University, Paderborn, Germany, June 3-7, 2019
	Upper and Lower bounds in Quantum Key Distribution	QTS 2019, Montreal, QC, Canada, July 1-5, 2019
	Quantum Communication with Coherent States of Light	Paderborn University, Paderborn, Germany, July 9, 2019
	Quantum Communication with Coherent States of Light	University of Vienna, Austria, December 4, 2019
Matteo Mariantoni	Gates and Dissipation in Superconducting Quantum Circuits	IQC, TQT Information Session, Waterloo, ON, Canada, December 12, 2019
	DEMUXYZ Gate Using Single Microwave Drive Line for Multiple Qubits, Materials and Processes for Quantum Information	Contributed Oral Address – AVS 66th International Symposium & Exhibition, Greater Columbus Convention Center, Columbus OH, USA, October 20-25, 2019
	Reducing Two-Level State Defects in Superconducting Resonators and Qubits	2019 MRS Spring Meeting & Exhibit, Phoenix Convention Center, Phoenix AZ, USA, April 22-26, 2019
Guo-Xing Miao	Layered Topological Materials	Quantum Technology: Academia Meets Industry, Shanghai University, Shanghai, China, September, 2019
	Mobilizing Lithium Ions towards Data Applications	Shandong Agricultural University, Taiwan, China, April, 2019

Faculty Member	Title/Subject	Institution/Conference
	Mobilizing Lithium Ions towards Data Applications	Institute of Physics, Chinese Academy of Science, Beijing, China, April, 2019
Michele Mosca	Toward A More Secure Quantum Future	Blockchain Technology Symposium, Toronto, ON, Canada, February 28, 2020
	Quantum Computing and IT Security	Fraunhofer Institute for Secure Information Technology (SIT), Darmstadt, Germany, January 28, 2020
	Toward a Quantum-Safe Future	CASA Distinguished Lecture Series, University of Bochum, Bochum, Germany, January 27, 2020
	The Context of Quantum Security	IDQ Winter School on Quantum Cybersecurity, Geneva, Switzerland, January 25, 2020
	Quantum Computing Update	ASC X9 Webinar (online), January 23, 2020
	Security in the Quantum Era	CROSSING Conference 2019, Darmstadt, Germany, September 9-10, 2019
	Cyber Talent, Skills and Quantum Readiness	CIO Strategy Council Member's Meeting, Toronto, ON, Canada, January 8, 2020
	Cyber Security Competency Group (CSCG) Competency Call – Post Quantum Computing (PQC) Readiness Planning	Cyber Security Competency Group (CRCG) Webinar (Online), December 19, 2019
	Quantum Computing	Institute for International Finance (IIF) Annual Membership Meeting, Washington, DC, United States, October 18, 2019
	Made in Canada- the significance of Canadian Security Technology	SecTor2019, Toronto, ON, Canada, October 10, 2019
	Security in the quantum future	Public Lecture, Entangled Series, Institute for Quantum Computing, Waterloo, ON, Canada, September 26, 2019
	Preparing for opportunity and security in the age of quantum	Round Table discussion on Security and Strategies in the Quantum Age at Lazaridis School Executive Development Centre, Kitchener, ON, Canada, September 19, 2019
	Understanding the current landscape, threats and opportunities posed to secure communications by quantum computing	Quantum Tech conference, Boston, MA, USA, September 11-12, 2019
	Building a more secure quantum future	9th International Conference on Quantum Cryptography (QCrypt2019), Montreal, QC, Canada, August 26, 2019
	All Hands on Deck for a Security Incident	True North Workshop, Waterloo, ON, Canada, June 20, 2019
	Quantum Computing	Financial Stability Board (FSB) Financial Innovation Network Meeting, Toronto, ON, Canada, June 18, 2019
	Toward a safe quantum future	ETSI Security Week-Cybersecurity Landscape, Sophia Antipolis, France, June 17, 2019
	Entering the era of quantum computing: challenges and opportunities	2019 University of Waterloo alumni weekend, Waterloo, ON, Canada, June 1, 2019
	Quantum computing and cybersecurity: challenges and opportunities	MS2 Seminar at Wilfrid Laurier University, Waterloo, ON, Canada, April 29, 2019
	Post-Quantum Crypto track: Update on the quantum threat and managing quantum	International Cryptographic Module Conference, Vancouver, BC, Canada, April 15, 2019
	Two Technologies: The Quantum and Blockchain Cyber Steam Trains - Swot Analysis	ICRMC (5th Annual International Cyber Risk Management Conference U.S. & Canada), Toronto, ON, Canada, April 16, 2019
	Quantum Cryptanalysis of Post Quantum Cryptography	University of Berkeley, Berkeley, CA, USA, February 22-24, 2020

Faculty Member	Title/Subject	Institution/Conference
	Quantum algorithms for analysis of public-key crypto workshop	American Institute of Mathematics, San Jose, CA, USA, February 4-8, 2020
	IQC Cybersecurity Symposium	Toronto, ON, Canada, December 17, 2019
	Seventh ETSI-IQC workshop on Quantum-Safe Cryptography	Seattle, WA, USA, November 5-7, 2019
	Dagstuhl seminar 19421 on Quantum Cryptanalysis	Leibniz Center for Informatics, Dagstuhl, Germany, October 13-18, 2019
	MathCrypt2019	Santa Barbara, CA, USA, August 18, 2019
	IQC Cybersecurity Symposium	Ottawa, ON, Canada, June 11, 2019
Christine Muschik	How to simulate lattice gauge theories on quantum computers	Simons Foundation, New York, NY, USA, December 5, 2019
	Quantum error correction by dissipation	Kavli Institute for Theoretical Physics, Santa Barbara, USA, May 3, 2019
	Quantum encryption and quantum communication	University of Washington, Seattle, USA, April 30, 2019
	How to simulate problems from high energy physics on quantum computers	Perimeter Institute, Waterloo, ON Canada, April 26, 2019
	Variational methods for quantum information processing	University of Chicago, Chicago, IL, USA, April 8, 2019
	CDQI ARL Program Review	Chicago, IL, USA, April 8, 2019
	NSAC QIS+QC Subcommittee: Meeting #2	University of Washington, Seattle, USA, April 30, 2019
	Quantum Computing Retreat	TRIUMF, Vancouver, BC, Canada, November 28, 2019
	Quantum Theory and Symmetries	Centre De Recherches Mathématiques, Montreal, QC, Canada, January 7, 2020
Ashwin Nayak	Participated in organizing not invited talks	34th Computational Complexity Conference (CCC 2019), New Brunswick, NJ, USA, July 17-20, 2019
	Participated in organizing not invited talks	IQC-IRIF mini-workshop on Quantum Algorithms and Complexity, Oct. 25, 2019
Vern Paulsen	Operator Algebras and Non-local Games, short course	University of Madrid, Madrid, Spain, May 6-10, 2019
	C*-algebras and Non-local Games	Canadian Operator Symposium, Regina, SK, Canada, April 6, 2019
	Constant Gap for Self-Embezzlement	Canadian Math Society, Regina, SK, Canada, June 8, 2019
	Preservation of Joint Essential Matricial Range	Canadian Math Society, Regina, SK, Canada, June 9, 2019
	The Many Faceted Connes Embedding Conjecture	Banff International Research Station, Banff, AB, Canada, July 15-19, 2019
	Embezzlement of Entanglement	Banff International Research Station, Banff, AB, Canada, July 15-19, 2019
	C*-algebras and Non-local Games	Mathematisches Forschungsinstitut, Oberwolfach, Germany, August 13, 2019
	Bisynchronous Games	University of Edinburgh, Scotland, UK, September 9, 2019
	Algebras and Synchronous Games	CMSA, Harvard University, Boston, MA, USA, October 17, 2019
Dmitry Pushin	Structured Neutron Waves	Caltech High Energy Physics Seminar, California Institute of Technology, Pasadena, CA, USA, February, 2020
	Structured Neutron Waves	University of Kentucky, Lexington, KY, USA, January, 2020
	Structured Neutron Waves	McMaster BIMR Seminar, McMaster University, Hamilton, ON, Canada, December, 2019

Faculty Member	Title/Subject	Institution/Conference
	Structured waves: from neutrons to light	QANSAS2019, Acra, India, November, 2019
	Phase-grating moiré neutron interferometry	XNPIG2019, Sendai, Japan, October, 2019
	Structured Waves: From Matter to Light	Heinz Maier-Leibnitz Zentrum, Munich, Germany, July, 2019
	Phase Grating Neutron Interferometry	2nd Workshop on Matter-Wave Interferometry, Vienna, Austria, May, 2019
K. Rajibul Islam	Quantum simulation of 2D spin models in a linear chain of trapped ions	Center for Quantum Information and Control, University of New Mexico, NM, USA, May 2, 2019
	Quantum simulation of 2D and 3D spin systems in a linear chain of trapped ions	Canadian Association for Physicists (CAP) congress, Simon Fraser University, Burnaby, BC, Canada, June 6, 2019
	Quantum simulation of 2D and 3D spin models in a linear chain of ions	Many-body States and Dynamics workshop, Perimeter Institute, Waterloo, ON, Canada, June, 2019
	Quantum simulation of spin models in arbitrary spatial dimensions using a linear chain of ions	North American Conference on Trapped Ions (NACTI), University of Maryland, College Park, USA, July 22, 2019
	Quantum Simulation with Trapped Ions	QANSAS 2019, Dayalbagh Educational Institute, Agra, India, November 12, 2019
Michael Reimer	The future of on-demand entangled photon sources	EQEP 2019 - 7th International Workshop on Engineering of Quantum Emitter Properties, Berlin, Germany, December 11, 2019
	Quantum sensing and imaging	Transformative Quantum Technologies (TQT) Quantum Opportunities and Showcase, Delivering on the Quantum Promise, Waterloo, ON, Canada, December 5, 2019
	Quantum LIDAR Ranging and 3D Imaging	The IQC International Workshop on Quantum Illumination: From Theory to Practice, Waterloo, Canada, December 3, 2019
	Quantum devices: from the lab to the real-world	QANSAS 2019, International School on Quantum and Nano Computing Systems and Applications, Dayalbagh Educational Institute (DEI), Agra, India, November 11, 2019
	Quantum for health	Waterloo Innovation Summit, Waterloo, ON, Canada, October 1, 2019
	High efficiency entangled photon sources and single photon detectors based-on semiconductor nanowires	META 2019, 10th international Conference on Metamaterials, Photonic Crystal and Plasmonics, Special Session: Towards High Efficiency Detectors and Sources for Field-Ready Quantum Nanophotonics, Lisbon, Portugal, July 26, 2019
	Generation of entangled photons with a quantum dot	Spin Canada 2019, Montebello, QC, Canada, June 24, 2019
	Quantum photonic devices Seminar	NRC, Ottawa, ON, Canada, June 18, 2019
	Next generation quantum sensors	Centre for Bioengineering & Biotechnology (CBB), Clinical Applications of Medical Imaging Technologies, Waterloo, ON, Canada, April 10, 2019
	On-demand generation of bright entangled photon pairs "Photon Qubit Entanglement and Transduction"	Advanced Photon Source (APS) and Center for Nanoscale Materials (CNM) Users Meeting, Argonne National Laboratory, Chicago, IL, USA, May 7, 2019
William Slofstra	Approximate representation theory.	Lorentz Center, Leiden, The Netherlands, May, 2019
	Computational complexity and the quantum value of non-local games.	University of Copenhagen, Copenhagen, Denmark, May 2, 2019
	An introduction to nonlocal games and device-independent testing.	Fields Institute, Toronto, ON, Canada, June 21, 2019

Faculty Member	Title/Subject	Institution/Conference
	Perfect zero-knowledge in MIP* protocols.	IQC, Waterloo, ON, Canada, October 25, 2019
Adam Wei Tsen	Tunneling Probe of Two-Dimensional Magnetism	Department of Physics and Astronomy Condensed Matter Seminar, University of California, Riverside, CA, USA, February 6, 2020
	Tunneling Probe of Two-Dimensional Magnetism	Department of Physics and Astronomy Condensed Matter Seminar, University of California, Irvine, CA, USA, February 5, 2020
	Tunneling Probe of Two-Dimensional Magnetism	School of Mathematics and Physics Seminar, Queen's University, Belfast, UK, January 22, 2020
	Tunneling Probe of Two-Dimensional Magnetism	Material Research Science and Engineering Center Seminar, Columbia University, New York, NY, USA, September 17, 2019
	Two-Dimensional Magnetism and Spintronics	UW Quantum Materials Workshop, University of Waterloo, ON, Canada, July 26, 2019
	Two-Dimensional Magnetism and Spintronics	UW-HKUST Workshop: Emerging Quantum Technologies in Solid-State and Atomic Systems, University of Waterloo, ON, Canada, July 23, 2019
	Two-Dimensional Magnetism and Spintronics	Department of Physics Condensed Matter Seminar, University of Virginia, VA, USA, May 30, 2019
Joel Wallman	Quantum Instructions	IARPA technical exchange meeting, Alexandria, USA, January 13, 2020
	Contextuality, Quantum Computation, and the Church of the Larger Hilbert Space	Quantum Physics and Logic, Orange, USA, June 12, 2019
	Reconstructing Pauli Error Channels	Quantum Computing Theory in Practice, Bristol, UK, April 9, 2019
John Watrous	Mathematics of Quantum Information	Cissy Patterson Lecture, Department of Mathematics, College of William and Mary, Williamsburg, Virginia, USA, April 5, 2019
Jon Yard	Fault-tolerant quantum gates: Constructions, applications and challenges	IQC Faculty Seminar, University of Waterloo, ON, Canada, November 22, 2019

H. Seminars & Colloquia

Colloquia	Speaker
Custom low-dimensional material systems explored at the atomic scale	Adina Luican-Mayer
Women in science meet and greet and the quantum steampunk	Nicole Yunger Halpern
Duality quantum computing: Computing with linear combinations of unitaries	Gui-Lu Long
A rare-earth ensemble quantum memory for scalable quantum computing	Byoung Ham
Quantum memories and Schrödinger's cat	Stephen Bartlett
A separation between QNCo and ACo	Adam Bene Watts
Renyi entanglement entropy in quantum many-body systems	Yichen Huang
Topological phases in transition metal chalcogenides	Junwen Liu
Superfluids of light	David Snoke
Quantifying the magic resources for quantum computation	Xin Wang
Optimization and cryptography in generalized physical theories	Jamie Sikora
Carbon-based nanoelectromechanics: Physics and applications	Sangwook Lee
Flexible, stretchable and healable bioelectronics	Fabio Cicoira
Transmitting and teleporting quantum-dot spin states	John Nichol
Lattice gauge quantum field theories in the age of quantum computers	Pavel Lougovski
Interfacing spins and photons in solids: Old friends and new	Mete Atature
Incompressibility of classical distributions	Debbie Leung
Quantum information processing with spins in cold atomic ensembles	Ivan Deutsch
New insights about quantum approximate counting	Scott Aaronson
Variational quantum algorithms: obstacles and opportunities	Sergey Bravyi
Quantum interference enables constant-time quantum information processing	Magdalena Stobinska

Seminars	Speaker
Quantum-inspired sublinear algorithms for solving low-rank linear systems and SDPs	Chunhao Wang
Dynamical phenomena in the electronic noise of a metallic wire	Bertrand Reulet
Computational intelligence: An introduction and a quantum vision	Giovanni Acampora
Quantum thermodynamics and superadiabatic control of complex systems	Aurélia Chenu
Toward inertial navigation with hybridized matter-wave interferometers	Brynle Barrett
Can we trust the outputs of a noisy quantum computer?	Sam Ferracin
Quench dynamics in optomechanical arrays: Simulation of non-equilibrium dynamics	Sadegh Raeisi
Building a single molecule from a reservoir of two atoms	Lee Liu
An optical tweezer phonon laser and the generation of mechanical coherent states	Mishkat Bhattacharya
Phase competition in thin magnetic oxide films: is the dead layer truly "dead"?	Robbyn Trappen
Efficient ansatz for quantum process tomography	Luke Govia
On optimality of CSS codes for Transversal T	Narayanan Rengaswamy
New methods for studying positivity and non-additivity of quantum capacities	Vikesh Siddhu
Study of charge current and spin current in van-der Waals 2-dimensional materials	Ghulam Dastgeer
SU(2) gauge theory on digital quantum computers	Jesse Stryker
Quantum Transport in topological superconductor hybrid systems	Bhaskaran MuralidharanIndian
Fine-grained quantum supremacy	Tomoyuki Morimae
Integrated optics for high-fidelity and parallelizable trapped-ion quantum logic	Karan Mehta
Calculating nature naturally	Natalie Klco
The interplay of strain, pressure, superconductivity, and topology in Weyl semimetal $MoTe_2$	Colin Heikes
Study of several quantum devices	Rui Yang
Phase transitions of quantum annealing and quantum chaos	Kazuki Ikeda
Quantum computation and simulation by Hamiltonian and dissipation engineering	Chiao-Hsuan Wang
Mitacs: Supporting collaborative research and innovation	Daniel Giovannini

Quantum nonlinear optics with Rydberg polaritons	Wenchao Xu
Quantum steampunk: Quantum information meets thermodynamics	Nicole Yunger Halpern

Student Seminars	**Speaker**
If (NMRSpin == 1): QState = QState + 1	Michael Chen
Qudit quantum error-correction	Lane Gunderman
Partitioning pauli operators: In theory or in practice	Andrew Jena
Equiangular lines	Sam Winnick
Simulating the dynamics of time-dependent Hamiltonians with a truncated Dyson series	Maria Kieferova
Rotating wave approximation and its causality consequences	Nicholas Funai
Electromagnetically induced transparency and Autler-Townes splitting in superconducting quantum circuits	Huichen Sun
ψ-epistemic interpretations of quantum theory have a measurement problem	Josh Ruebeck
Introduction to adiabatic quantum computation and quantum annealing	Xi Dai
Variational quantum state diagonalization	Étude O'Neel-Judy
NP-complete optimisation problems on the D-Wave quantum annealer	Esha Swaroop
The art of post-truth in quantum cryptography	Sara Zafar Jafarzadeh
An introduction to computational complexity theory	Raphael Koh
Quantum games with competing provers	Soumik Ghosh
An introduction to continuous-variable quantum key distribution with discrete modulation	Jie Lin
Linear system non-local games and their graphs	Connor Paul-Paddock
Recent results using quantum kernel methods	Evan Peters
Locality of temperature and correlations in the presence of non-zero-temperature phase transitions	Senaida Hernández Santana
Deterministic single photon subtraction	Supratik Sarkar
The mathematical structure behind the Binary Linear System games	Junqiao Lin
Quantum memories with multi-photon gates using Rydberg and artificial atoms	Andrew Koehler Hardy
On the landscape of near-term quantum computers	Jessica Pointing
Quantum experiments with single-photon spin-orbit lattice arrays	Ruoxuan Xu
Structured neutron waves	Connor Kapahi
Erasable bit commitment with temporarily trusted parties	Ashutosh Satyajit Marwah
Numerical finite key rates for general QKD protocols	Ian Thomas George
Causal order as a resource for quantum communication	Ding Jia
Independent characterization of state and measurement processes	JunAn Lin
Machine learning QFT with local probes	Daniel Grimmer
Quantum heat engine operating between thermal and spin reservoirs	Salil Bedkihal
A gradient-based method for controlling adiabatic trajectories	Arthur Pesahas
Graph states in quantum metrology	Nathan Shettell
The garden-hose model of communication complexity	Alex Kerzner
Tomography with Young Tableaux	John Bostanci

I. Scientific Visitors & Tours

Longer Term Visitors

Visitor Name	Visitor Affiliation
Scott Aaronson	University of Texas, Austin
Giovanni Acampora	University of Naples Federico II
Mete Atature	The University of Cambridge
Artur Avkhadiev	Perimeter Institute
Yosri Ayadi	University of Sherbrooke
David Bacco	Technical University of Denmark
Brynle Barrett	iXblue (France)
Stephen Bartlett	The University of Sydney, Australia
Thiago Bergamaschi	Massachusetts Institute of Technology
Mishkat Bhattacharya	Rochester Institute of Technology
Ali Binai-Motlagh	Dalhousie University
John Bostanci	Carnegie Mellon University
Sergey Bravyi	IBM Research
Margie Bruff	University of North Carolina at Chapel Hill
John Bruniston	The University of Calgary
Simon Carrier	University of Sherbrooke
Aixi Chen	Jiaotong University
Xi Chen	Hong Kong University of Science and Technology
Aurélia Chenu	Donostia International Physics Center
Che-Fu Chiang	New York Polytechnic Institute
Salvatore Chiavazzo	University of Trieste
Anirban Ch Narayan Chowdhury	University of Sherbrooke
Fabio Cicoira	Polytechnique Montreal
Ghulam Dastgeer	Sejong University
Amanda Davenport	University of Minnesota
Li Deng	East China Jiaotong University
Ivan Deutsch	University of New Mexico
Ying Dong	Hangzhou Normal University
Gabriel Ethier-Majcher	Anyon Systems Inc.
Kate Fenwick	University of Ottawa
Sam Ferracin	University of Warwick
Henry Fetsch	Harvey Mudd College, Claremont California
Virginia Frey	The University of Sydney
Steven Gassner	SUNY Polytechnic Institute
Sevag Gharibian	University of California, Berkeley
Francesco Ghisoni	King's College London
Tasio Gonzalez Raya	University of Basque Country, Spain
Luke Govia	Raytheon-BBN Technologies
Don Hadwin	The University of New Hampshire
Byoung Ham	Gwangju Institute of Science and Technology

Visitor Name	Visitor Affiliation
Yassine Hamoudi	Centre national de la recherche scientifique
Colin Heikes	NIST Center for Neutron Research (NCNR)
Masahiro Hotta	Tohoku University
Yichen Huang	Microsoft Research
Kazuki Ikeda	Osaka University
Joe Iverson	California Institute of Technology
Daniel James	University of Toronto
Alan Jamison	Massachusetts Institute of Technology
Karl Jansen	NIC/DESY Zeuthen, Germany
Daniel Kang	Kyoto University
Pradip Kattel	Howard University
Natalie Klco	Institute for Nuclear Theory, The University of Washington
Robin Kothari	Microsoft Research
Sukanya Kudva	Indian Institute of Technology Bombay
Danny Kun	Institute for Theoretical Physics ETH Zurich
Srijita Kundu	Centre for Quantum Technologies, National University of Singapore
Kohdai Kuroiwa	University of Tokyo
Paul Kwiat	University of Illinois at Urbana-Champaign
Jonas Landman	Centre national de la recherche scientifique
Jan-Åke Larsson	Linköping University
Arne Laucht	University of New South Wales
Sangwook Lee	Ewha Womans University
Jeremy Levick	Conestoga College/University of Guelph
Randy Lewis	York University
Lin Li	Anyon Systems Inc.
Qiang Li	Qingdao University
Junwei Liu	Hong Kong University of Science and Technology
Lee Liu	Harvard University
Gui-Lu Long	Tsinghua University
Ulises Alejandro Lopez	University of Buenos Aires
Pavel Lougovski	Oak Ridge National Laboratory
Dawei Lu	University of Science and Technology of China
Adina Luican-Mayer	University of Ottawa
Alessandro Luongo	Centre national de la recherche scientifique
Haiqiang Ma	Beijing University of Posts & Telecommunications
Xiongfeng Ma	Tsinghua University
Frederic Magniez	Centre national de la recherche scientifique
Sonell Malik	Indian Institute of Science Education and Research, Mohali, Punjab
Tanja Maric	Nicolaus Copernicus University
Damian Markham	Centre national de la recherche scientifique
Brian McMinn	University of Pittsburgh
Karan Mehta	Institute for Theoretical Physics ETH Zurich
Belota Moreno	Amherst College
Karen Morenz	University of Toronto
Tomoyuki Morimae	Kyoto University
Shahabeddin Mostafanazhad Aslmarand	Florida Atlantic University

Visitor Name	Visitor Affiliation
Phani Muppalla	Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck
Bhaskaran Muralidharan	Indian Institute of Technology Bombay
Anand Natarajan	California Institute of Technology
John Nichol	University of Rochester
Lara Ostertag	University of Southern California, Berkeley
Michal Oszmaniec	Center for Theoretical Physics PAS
Clauderic Oullett-Plamondon	Anyon Systems Inc.
Zachary L. Parrott	Colorado School of Mines
Yawen Peng	University of Science and Technology of China
Chithrabhanu Perumangatt	National University of Singapore
Sadegh Raeisi	Department of Physics, Sharif University of Technology
Venu Reddy	Anyon Systems Inc.
David Reichmuth	Heriot-Watt University
Narayanan Rengaswamy	Duke University
Bertrand Reulet	University of Sherbrooke
Jeremie Roland	Ecole Polytechnique de Bruxelles
Abhisek Sahu	Indian Institute of Technology Bombay
Mai Sakuragi	Oregon State University
Jose Sanchez Velasquez	Universidad Autónoma de Madrid
Martin Savage	Institute for Nuclear Theory, Washington
Phiala Shanahan	Massachusetts Institute of Technology
Nathan Shettell	Osaka University
Vikesh Siddhu	Carnegie Mellon University
Dogan Sinar	Western University
David Snoke	University of Pittsburgh
Haly So	Columbia University
Jalex Stark	Jane Street Group, New York City
Magdalena Stobinska	University of Warsaw
Jesse Stryker	The University of Washington
Esha Swaroop	Birla Institute of Technology and Science, Pilani
Daniel Szilagyi	Centre national de la recherche scientifique
Jakub Szlachetka	Nicolaus Copernicus University
Ernest Tan	Institute for Theoretical Physics ETH Zurich
Bing Teng	Qingdao University
Robbyn Trappen	West Virginia University
Robert Trenyi	University of Vigo, Spain
Alain Emiel Cornelis Van den Bosch	Technical University of Eindhoven
Joao Marcos Vensi Basso	Tufts University
Yidun Wan	Fudan University
Chiao-Hsuan Wang	University of Chicago
Chunhao Wang	The University of Texas, Austin
Hongyu Wang	Fudan University
Xin Wang	University of Maryland
Adam Bene Watts	Massachusetts Institute of Technology
Andrea Wei Coladangelo	California Institute of Technology
James Wojtyk	Privy Council Office, Government of Canada
John Wright	Massachusetts Institute of Technology
Wenchao Xu	Massachusetts Institute of Technology

Visitor Name	Visitor Affiliation
Rui Yang	Southern University of Science and Technology, China
Alireza Yazdi	Anyon Systems Inc.
Nicole Yunger Halpern	Harvard University Department of Physics (Institute for Theoretical Atomic, Molecular, and Optical Physics)
Mujtaba Zahady	Universita degli studi di Padova, Padova, Italy
Jingfu Zhang	Technische Universitat Dortmund
Deyi Zhou	University of Science and Technology of China
Peter Zoller	University of Innsbruck

K. Financial – Auditor's Report

Audited statements are not yet available. An auditor's report will be submitted to ISED upon completion.