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UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

INSTITUTE FOR QUANTUM COMPUTING
ANNUAL REPORT for APRIL 1, 2018 – MARCH 31, 2019

Report for University of Waterloo Board of Governors approval

TO BE SUBMITTED TO:
THE MINISTRY OF INNOVATION, SCIENCE AND ECONOMIC DEVELOPMENT
JULY 30, 2019

FROM THE EXECUTIVE DIRECTOR

Canada's Quantum Opportunity

2018-2019 has been a fantastic year for the Institute for Quantum Computing. The generous support from the Government of Canada has enabled IQC to make scientific breakthroughs, train the quantum workforce, support industrial growth and develop commercialization opportunities, all while fostering an inclusive space for people to work and study.

IQC is unique in the world for its scope of expertise, quality of infrastructure, and range of scientific equipment. We have created a vibrant community of researchers with a shared focus on solving the toughest problems quantum poses. IQC is the hub of Waterloo's Quantum Valley, a technology cluster dedicated to advancing quantum technologies that aims to maximize the benefits of the quantum economy for Canada. The investment from the Government of Canada helps us to attract and train talented researchers and provide them with the tools required to advance our understanding and develop new technologies that will drive the next quantum revolution.

I'm immensely proud of what IQC has achieved and excited about the future. We look forward to continuing to work alongside the Government of Canada to advance quantum research and enable Canada to capitalize on the quantum opportunity.

Kevin Resch
Interim Director
Institute for Quantum Computing
University of Waterloo

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ABOUT THE INSTITUTE FOR QUANTUM COMPUTING

IQC was created 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 has grown to become Canada's core quantum initiative for the next technological revolution – the quantum revolution. 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 three strategic objectives developed in partnership with the Ministry of Innovation, Science and Economic Development:

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

FUNDING OBJECTIVES 2017-2019

IQC was awarded $10M over two years through the generous support of the Government of Canada. This funding served to support 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;
C. Brand Canada as the destination of choice for conducting research in quantum technologies in order to attract the best in the world to Canada, create and strengthen partnerships with the international quantum information science community and promote 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 research in quantum information science can be applied; and
E. Increasingly translate research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada.

Expected Results

- Increase knowledge in quantum information science and technology;
- Support and create opportunities for students to learn and apply new knowledge;
- Brand Canada as a place to conduct research in quantum information technologies;
- Increase awareness and knowledge of quantum information science and technology and the Institute in both the scientific community and amongst Canadians more generally; and
- Position Canada to take advantage of economic and social benefits of quantum information science through seizing opportunities to commercialize breakthrough research.

Through the activities planned and undertaken with the contribution of the Government of Canada in the past years, IQC has positioned Canada to take advantage of economic, social, and in some cases, environmental benefits of quantum research. What follows is progress achieved in the 2018-2019 year.

2018-2019 ACHIEVMENTS AND RESULTS

Objective A

Increase knowledge in quantum information science and technology (Increase in 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 science and technology.

Planned Activities 2018-2019:

- Leveraging 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 up to two new faculty members.
- Recruit up to one new research assistant professor.
- 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 NanoFab facility to enable fabrication of quantum-enabled technologies.
- Update and maintain lab space in Research Advancement Centre (RAC) buildings.
- Continue effective and relevant relationships with current partners.
- Seek out new partnerships that will advance IQC's mission and strategic objectives.

Progress Achieved in 2018-2019

Continue a collaborative research agenda in quantum computation, quantum communication, quantum sensors and quantum materials

IQC researchers collectively pursue a collaborative and interdisciplinary research agenda resulting in advancements in our understanding of quantum information science and technologies. Following are short summaries on select research results from this past year. A full list of publications can be found in Appendix B, *Publications*, on page 42.

Mitigating leakage errors due to cavity modes in a superconducting quantum computer
Quantum Science and Technology
http://iopscience.iop.org/article/10.1088/2058-9565/aabd41/pdf

The Digital Quantum Matter (DQM) lab, led by researcher Matteo Mariantoni, studied two frequency-shifting techniques to prevent a quantum system's own hardware from interfering with qubit operation.

“As a quantum system is scaled up and gains qubits, it becomes more challenging to maintain the qubit states,” said Thomas McConkey, PhD candidate and lead author on the study. “And once a qubit system is large enough, its own hardware can cause information to leak out and the chip to stop functioning altogether.”

When a qubit chip is housed in a superconducting box, the box and chip dimensions often create unwanted modes that support different microwave frequencies. If the mode frequency is near the qubit frequency, information held in the qubit will transfer to this mode, causing processing errors.

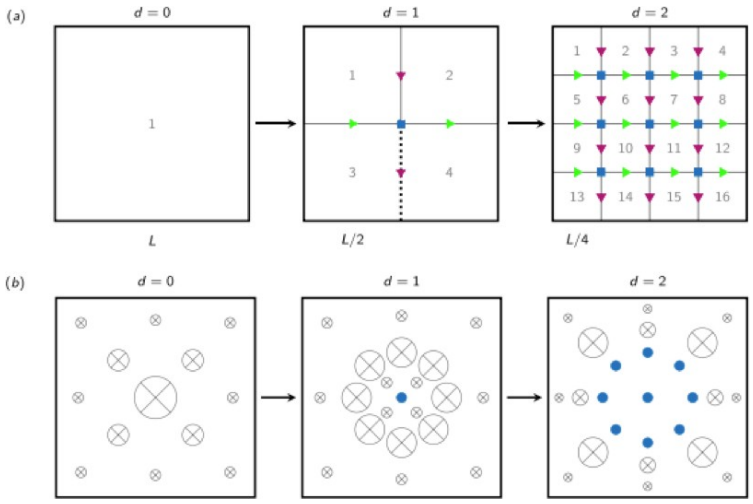


Figure 1: A) Half-wave fencing. B) Anti-node pinning.

The first solution proposed by DQM, anti-node pinning, is a familiar concept in the engineering world, but has never before been applied to quantum computing.

True to its name, anti-node pinning involves placing a pin at the anti-node of the first mode, resulting in a shift of its frequency. The pinning process is repeated until the resonance frequency of the mode shifts above the frequency of the qubit, lowering the leakage error rate.

While anti-node pinning gives optimal resource return and is compatible with any cavity shape, it results in pin arrangements that aren’t readily compatible with grid arrays of qubits. Since grid pattern chips are the designs that result from pursuing a variety of common quantum computing schemes like the surface code, the research group looked at a second method to shift the frequency: half-wave fencing. This approach creates multiple smaller cavities inside the original cavity, like a faraday cage.

Simulations testing the effectiveness of both frequency-shifting methods showed the leakage error rates could be easily lowered to orders of magnitude below the best overall error rates achievable in the field currently.

“The quantum socket shows a promising way to suppress spurious modes by strategically placing them in a cavity containing quantum circuits,” said Vivekananda Adiga, Research Engineer at IBM Research. “This can improve the control and readout of qubits by reducing leakage and crosstalk. It enables a potential path forward to extend the qubit lattices to large areas without compromising their performance.”

In the next phase of the project, researchers will test the frequency shifting methods in the lab.

“There are many other scaling issues under consideration, such as scalable qubit controllers, so there is still much more work to do,” said Mariantoni, also a professor in the Department of Physics and Astronomy at the University of Waterloo. “But at least we have methods to mitigate leakage errors.”

Mitigating leakage errors due to cavity modes in a superconducting quantum computer, is published in Quantum Science and Technology. This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund (CFREF).

Generating Multimode Entangled Microwaves with a Superconducting Parametric Cavity
Physical Review Applied
https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.10.044019

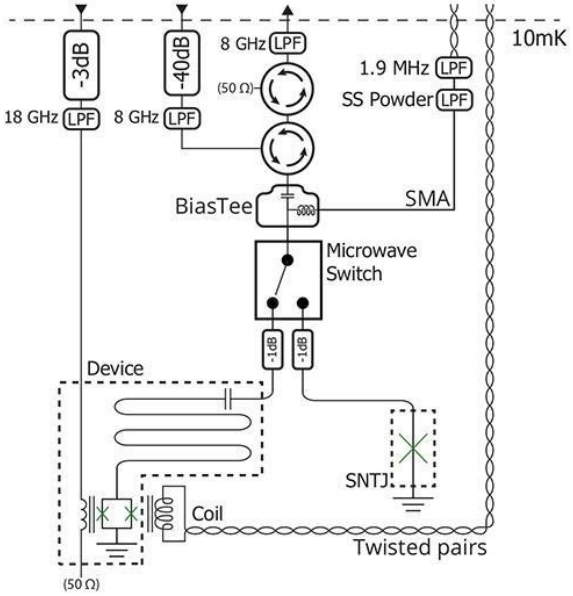
A team of researchers at the Institute for Quantum Computing (IQC) generated three-photon entanglement on a superconducting chip using a new, scalable technique.

The experiment, published in Physical Review Applied, could lead to advances in quantum communication protocols like secret sharing and in quantum computing power.

“Broadly, we want to distribute entanglement,” said IQC Professor Chris Wilson, who led the study with the Engineered Quantum Systems Lab (EQSL) team. “That could mean extending it over very long distances for secure communication, or it could also mean distributed entanglement on a quantum processor to different sections of a computer chip.” To generate multiphoton entanglement the team relied on quantum states of microwave light operating at frequencies near 5 GHz-- the same frequency band as wireless communications used by cellphones and Wi-Fi connections. The team designed a special superconducting circuit that acts as a microwave cavity.

“The cavity is like a box for storing photons,” explained Wilson, also a professor in the Department of Electrical and Computer Engineering at the University of Waterloo. “This box can hold photons of a number of different frequencies."

The photons are entangled on the chip when high-frequency magnetic fields are applied to a superconducting quantum interference device (SQUID) integrated into the cavity, a process known as parametric down conversion. This changes the system’s electrical properties and, as a result, also the frequency of the photons in the microwave cavity.



A simplified schematic of the measurement setup.

When the frequency-changing signal is pumped into the circuit, the photons are split to create sets of photons that are entangled with each other. Changing the frequency also moves the photons between modes, or sections, of the circuit.

“If we apply a magnetic field at the sum of two cavity frequencies, the photons that are created each go into one of two modes, producing two photons of different frequencies, or different

colours, but they are still entangled." Wilson uses the analogy of a dancer dressed in red and another dressed in blue, but they are still moving in synchrony.

In the experiment performed at IQC, the EQSL team demonstrated three-photon entanglement. The new method, however, is easily extendable for adding more entangled quantum states.

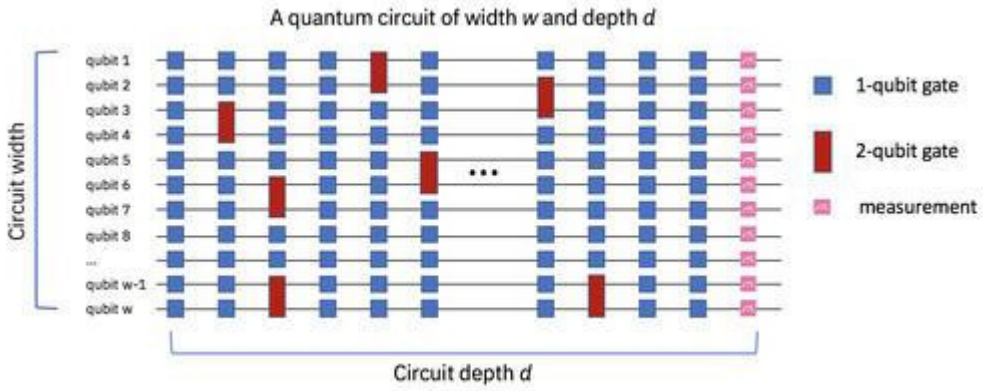
In addition to applications in performing secure quantum communication protocols, the results yield promising engineering advances for building a superconducting quantum computing platform.

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

Quantum advantage with shallow circuits
Science
http://science.sciencemag.org/content/362/6412/308

Quantum computers can solve a linear algebra problem faster than classical computers, according to a new study published in Science. The finding proves that constant-depth quantum circuits are more powerful than their classical counterparts, and provides a new sense of how quantum technology will be a key to more powerful computing.

The study, conducted by a team of researchers at IBM T.J. Watson Research Center including Sergey Bravyi, IQC faculty member David Gosset, and Robert König of the Technical University of Munich (TUM) could also guide the way toward promising use cases for the next generation of quantum computers.



Scientists prove there are certain problems that require only a fixed circuit depth when done on a quantum computer no matter how the number of inputs increase. On a classical computer, these same problems require the circuit depth to grow larger.

A quantum circuit performs a quantum algorithm by applying a sequence of gates that operate on a small number of qubits. Gates acting on different subsets of qubits can be applied in parallel at each time step, as specified by the algorithm. The number of time steps is called the circuit depth.

“Understanding the power of circuits with very shallow depth is relevant in understanding the power of near-term computers,” explained Gosset, also an associate professor in the Department of Combinatorics and Optimization at the University of Waterloo. Near-term quantum computers without error-correction are limited in the size of computations they can perform. “When you’re limited in size, you either look at a small number of qubits, shallow circuit depth, or both,” Gosset said.

The team of researchers considered constant-depth circuits, meaning that the depth or number of time steps is independent of the number of qubits. They discovered that a quantum computation with a constant number of time steps – a constant-depth quantum circuit – could solve a certain linear algebra problem which they call the 2D Hidden Linear Function problem.

Furthermore, they demonstrated that no classical computation of constant depth could solve the same problem, providing evidence of a quantum advantage over classical computers.

The quantum algorithm only requires circuits laid out on a two-dimensional grid, consistent with what is currently used in experimental settings, one-step closer to implementation on near-term devices.

The results also open up new possibilities for quantum algorithm development and raise the question of whether such a speedup can persist in the presence of noise processes that occur in currently available technology.

Generation of a Lattice of Spin-Orbit Beams via Coherent Averaging
Physical Review Letters
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.183602

and

Methods for preparation and detection of neutron spin-orbit states
New Journal of Physics
https://iopscience.iop.org/article/10.1088/1367-2630/aae3ac

Researchers at the Institute for Quantum Computing (IQC) in collaboration with researchers at the National Institute for Standards and Technology (NIST) have developed a highly robust method for structuring light and matter waves, enhancing the powerful probing ability of neutrons.

Controlling a property of light called Orbital Angular Momentum (OAM) has led to applications in communication, microscopy and manipulating quantum information. Recently, in two different studies, IQC researchers demonstrated a new method of structuring spin-coupled OAM that is more robust and offers new approaches to the study of magnetic and chiral materials.

In the first study, the researchers created a beam of light consisting of a lattice of spin-coupled OAM states. It is the first time that this technique has been applied to optics. To produce the spin-coupled OAM states of light, the researchers used coherent averaging and spatial control methods borrowed from nuclear magnetic resonance.

“Spin-coupled OAM states of light have been used in numerous applications such as achieving extremely high bandwidth data transmission,” explained Dusan Sarenac, technical lead for Transformative Quantum Technologies (TQT). “An enabling feature of our method would be to expand the capability of these beams by providing an array of such states, made available by the lattice structuring.”

The method is extendable to other mediums, such as neutrons. Neutrons are a powerful probe of materials with unique penetrating abilities and magnetic sensitivity, and are particularly powerful for characterizing the inner magnetic field structure of materials because they easily penetrate through materials that normally block light.

Extending the OAM structuring method to neutrons enhances their powerful probing ability and adds a new degree of freedom for material characterization with neutrons.

“The technique we introduce enables the neutrons to be used as a probe of new types of topological materials whose inner magnetic fields form helices,” said Sarenac, lead author on the paper. “It could lead to exciting advances in neutron optics and neutron imaging.”

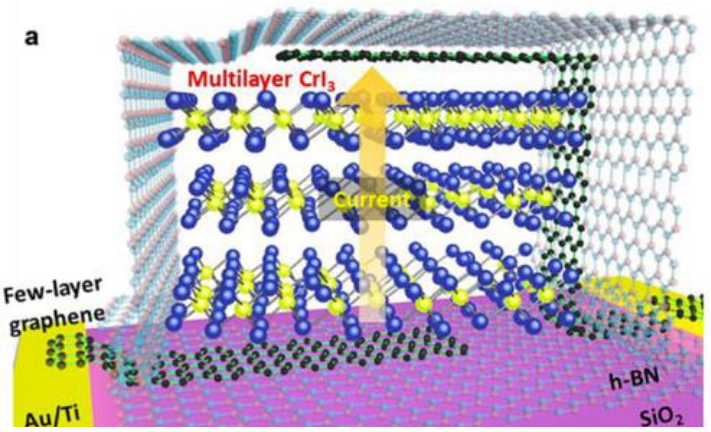
A new characterization method for neutrons was also introduced. The method can directly measure the correlations of spin state and transverse momentum, overcoming the major challenge associated with neutrons—low flux and small spatial coherence length.

“The hope is that this detection procedure can be extended to other probes such as electrons and X-Rays,” said Sarenac.

This research was undertaken thanks in part to funding from CFREF.

One Million Percent Tunnel Magnetoresistance in a Magnetic van der Waals Heterostructure
Nano Letters
https://pubs.acs.org/doi/10.1021/acs.nanolett.8b01552

A team of IQC researchers led by faculty member Adam Wei Tsen and postdoctoral fellow Hyun Ho Kim, in collaboration with the Renmin University of China, demonstrated an electronic device with an extremely large response to a magnetic field by using a combination of two-dimensional quantum materials. The size of this effect was unexpected, and may provide avenues for further development of quantum technologies.



Schematic of the magnetic tunnel junction created by the researchers. The hexagonal boron nitride (h-BN) enclosure protected the chromium tri-iodide from environmental effects.

Quantum materials have exotic properties that can help build novel devices. Two-

dimensional (2D) materials are a case in point: they are only a few atoms thick and often exhibit different properties than their 3D counterparts.

“Imagine stripping individual compounds down to the single layer limit, and then artificially recombining them to form heterostructures,” said Tsen. “These are new material systems that cannot be directly grown. When you put together different materials like this, new physical phenomena can emerge.”

The researchers observed a one million percent tunnel magnetoresistance in a device called a magnetic tunnel junction made with chromium tri-iodide (CrI_3), graphene, and boron nitride. “At first, we just wanted to understand the magnetic properties of CrI_3, which is what this device geometry would let us do,” said Tsen, also a professor in the Department of Chemistry in the Faculty of Science. “When we applied a small magnetic field, we saw a huge change in device resistance, and so we decided that this was something worth investigating.”

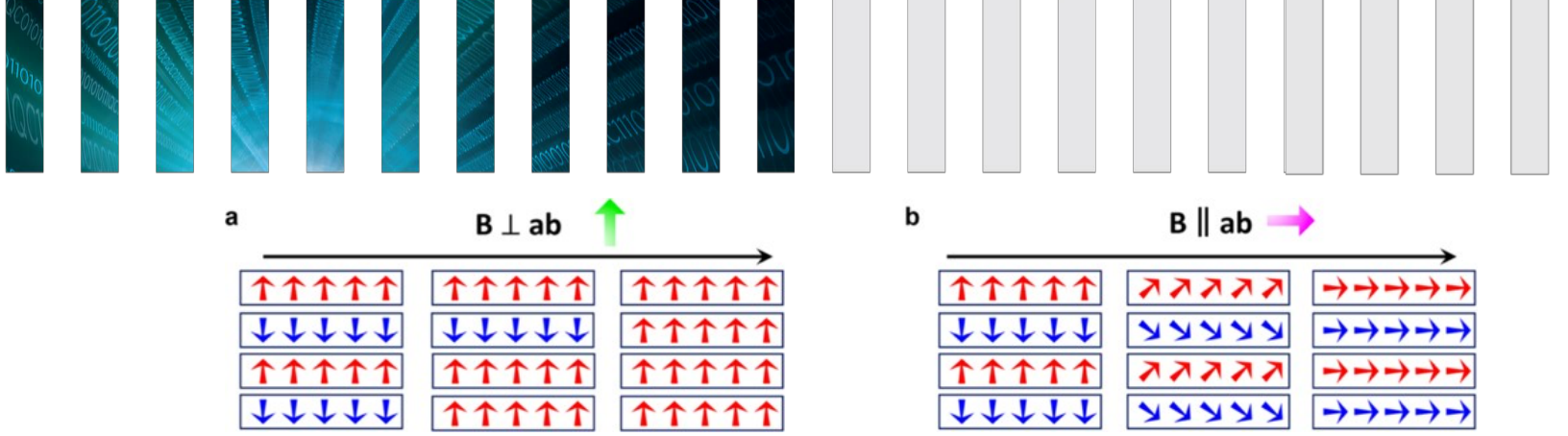
Magnetic tunnel junctions typically consist of two ferromagnets (inherently, strongly magnetic metals) separated by a thin layer of insulator. When a voltage is applied across the junction, electrons can actually tunnel through the ultra-thin insulator, thanks to quantum mechanics. Switching between parallel and antiparallel magnetizations in the ferromagnets changes electrical resistance in the insulator from low to high. This is tunneling magnetoresistance.

Magnetic tunnel junctions are used in magnetoresistance random access memory (MRAM). By assigning a 0 and a 1 to the high and low resistance states, MRAM can be used as both computer storage and memory.

Interested in what would happen if the semiconductor itself was layered and magnetic, the researchers made the magnetic tunnel junction by manually placing 2D layers of the magnetic semiconductor CrI_3 between graphene electrodes. When a voltage was applied across the tunnel junction, electrons quantum-tunneled through the thin layer of CrI_3.

In a low-temperature environment, the team then introduced a magnetic field. That is when something interesting happened: the electric current passing through the junction increased by one million percent.

Coupling between layers of 2D CrI_3 is, unlike with its 3D counterpart, antiferromagnetic: each layer has an opposite spin to the one above and below it. This creates a high barrier to electron tunneling. When the researchers introduced a magnetic field, it aligned the spins of each layer, which reduced the tunnel barrier and allowed for a dramatically reduced electrical resistance of the semiconductor.



Progression of the polarization of spins in each layer of chromium tri-iodide with the introduction of a magnetic field. Diagram a) represents the change with a perpendicular magnetic field, while b) represents the change with a parallel one.

The researchers observed magnetoresistance several orders of magnitude larger than that of current tunnel junctions used in commercially available MRAM. The observation of this sizable magnetoresistance and fine spin control opens up a path for further research with this quantum material that could lead to advances in spintronics.

The paper, One Million Percent Tunnel Magnetoresistance in a Magnetic van der Waals Heterostructure, appeared in Nano Letters.

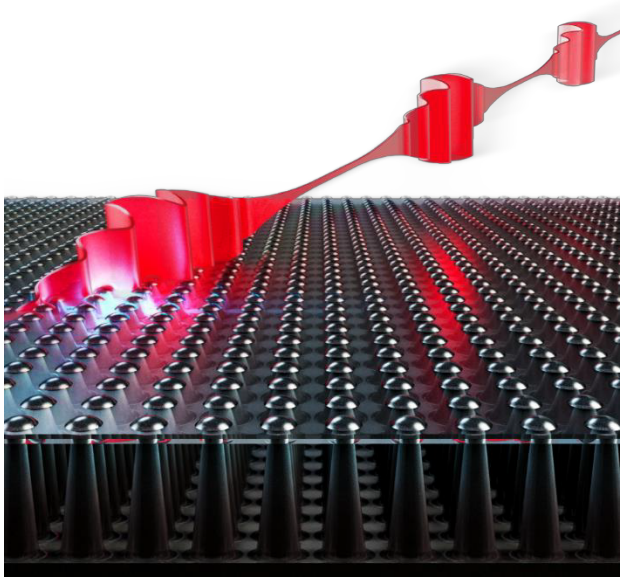
This research was undertaken thanks in part to funding from CFREF.

Tapered InP nanowire arrays for efficient broadband high-speed single-photon detection
Nature Nanotechnology
https://www.nature.com/articles/s41565-019-0393-2

Researchers at the IQC, led by faculty member Michael Reimer, have developed a new quantum sensor based on semiconductor nanowires that can detect single particles of light with high speed, timing resolution and efficiency over an unparalleled wavelength range, from ultraviolet to near-infrared.

The world-first device outperforms existing commercial technologies and promises enormous possibilities for sensing applications including dose monitoring for cancer treatment, 3D imaging, quantum communication and remote sensing.

“A sensor needs to be very efficient at detecting light. In applications like quantum radar, surveillance, and nighttime operation, very few particles of light – called photons – return to the device,” says Reimer, also an assistant professor in the Department of Electrical and Computer Engineering at the University of Waterloo. “In these cases, you want to be able to detect every single photon coming in.”



Artist's representation of the interaction of incident single photon pulses and a tapered semiconductor nanowire array photodetector. Each nanowire is shaped in an optimal way to strongly absorb the incoming light. A blue glow shows an artistic impression of the absorption process and avalanche effect in the nanowire p-n junction.

The next generation quantum sensor designed in Reimer's Quantum Photonics Devices Lab is so fast and efficient that it can absorb and detect a single photon and refresh for the next one within nanoseconds.

The researchers created an array of tapered nanowires that turn incoming photons into electric current that can be amplified and detected. The semiconducting nanowire array achieves its high speed, timing resolution and efficiency thanks to the quality of its materials, the number of nanowires, doping profile and the optimization of the nanowire shape and arrangement.

The researchers used advanced modelling software to optimize the shape of the nanowires. The tapered design allows for high bandwidth detection because shorter wavelengths of light are absorbed at the top of the nanowire and longer wavelengths are absorbed near the bottom. Their design also allows photons to be absorbed right at the positive-negative (p-n) junction of the nanowire that generates the electric field necessary to amplify the absorbed photon. Absorption at the p-n junction means less time travelling along the nanowire and higher timing resolution, which is necessary for detecting each individual photon with high timing accuracy.

The team's collaborators at the Eindhoven University of Technology in the Netherlands found that etching the nanowires resulted in higher optical quality than growing them from the bottom-up. These nanowires allow for a very low dark current—the default noise before photon absorption—meaning that the researchers achieve an excellent signal-to-noise ratio.

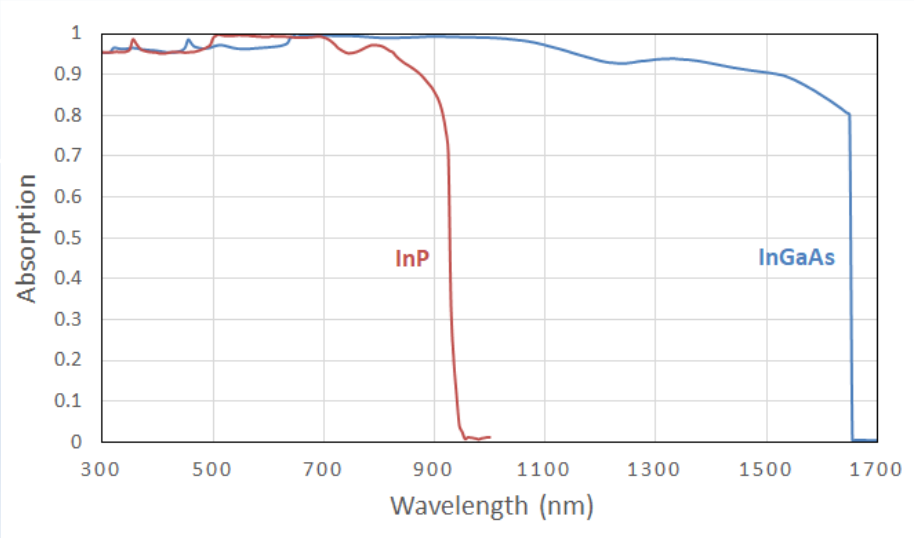
Reimer and his team optimized the arrangement of the nanowire array to achieve a fast response time. "We found that if the nanowires were too far apart, light would just pass through undetected," explains Reimer. "If they were too close together, then they acted as a bulk material and reflected the light. With the right spacing and the shape, the array doesn't reflect and instead absorbs all the light."

Remote sensing, high-speed imaging from space, acquiring long-range high-resolution 3D images, quantum communication, and singlet oxygen detection for dose monitoring in cancer treatment are all applications that could benefit from the kind of robust single photon detection that this new quantum sensor provides.

Single photon detectors using superconducting nanowires have been developed to meet many of the demands of these applications, but their portability is limited due to their cryogenic operating temperatures. This constraint relegates these devices to the lab.

Single photon avalanche photodiodes currently on the market overcome the problem of temperature, but require trade-offs between timing resolution and efficiency. The new array of nanowires developed by Reimer and his team require no such compromises. They detect light with high efficiency and high timing resolution, and achieve these results at room temperature. Reimer notes that operation beyond the lab will likely benefit from a simple and portable Peltier cooler lowering the temperature of the device somewhere below zero, a far cry from the roughly three Kelvin required by available superconducting devices.

Unlike commercially available single photon detectors that only absorb a narrow bandwidth of light, this new sensor can detect a broad spectrum from ultraviolet (UV) to near infrared (IR). Reimer predicts this range can be broadened even further towards telecommunication wavelengths.



"This device uses Indium Phosphide (InP) nanowires. Changing the material to Indium Gallium Arsenide (InGaAs), for example, can extend the bandwidth even further while maintaining performance," says Reimer. "It's state of the art now, with the potential for further enhancements."

Absorption spectrum of InP nanowire array and InGaAs nanowire array showing near-unity absorption over an unprecedented wavelength range.

This extended range will allow detection of telecommunication and IR wavelengths, expanding the range of feasible commercial applications even further.

With an efficient, high speed, broadband, room temperature quantum sensor at their fingertips, what could be next for these researchers?

Once the prototype is packaged with the right electronics and portable cooling, the sensor is ready for testing beyond the lab. "A broad range of industries and research fields will benefit from a quantum sensor with these capabilities," says Reimer. "This efficient, high speed, broadband, room temperature quantum sensor opens the door to exciting new possibilities for photon detection."

The nanowire array was designed and fabricated in the Netherlands by collaborators at the Eindhoven University of Technology, and tested in the Quantum Photonic Devices lab at IQC. Tapered InP nanowire arrays for efficient broadband high-speed single photon detection was published in Nature Nanotechnology March 4. This research was undertaken thanks in part to funding from CFREF.

Quantum-enhanced noise radar
Applied Physical Letters
https://aip.scitation.org/doi/10.1063/1.5085002

Researchers at the Institute for Quantum Computing (IQC) performed the first demonstration of quantum-enhanced noise radar, opening the door to promising advancements in radar technology.

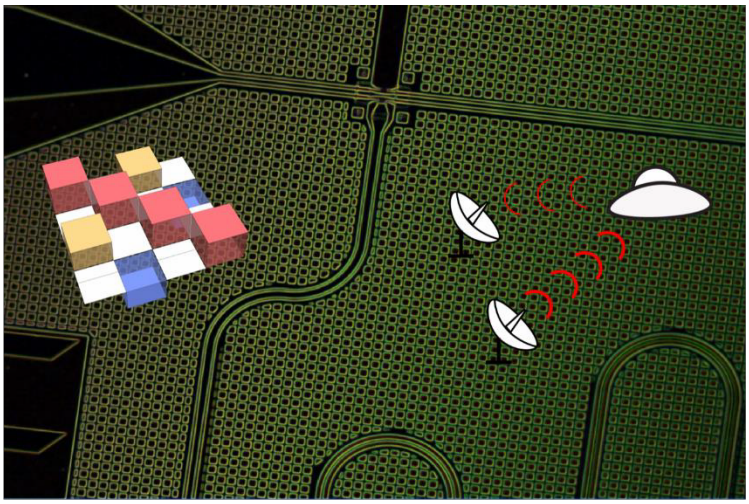
The researchers showed how the quantum process can outperform a classical version of the radar by a factor of 10, enabling the detection of objects that are faster, smaller, or further away – all while making the radar less detectable to targets.

“We are applying technology developed for quantum computing to immediate, practical situations,” said Christopher Wilson, a professor in the Department of Electrical and Computer Engineering at the University of Waterloo and principal investigator of the Engineered Quantum Systems Lab (EQSL) at IQC. “Our results show a promising improvement for radar, an important real-world application, using quantum illumination.”

In the lab, Wilson’s team performed a proof-of-principle radar detection experiment to directly compare the performance of a quantum protocol to a classical protocol. The researchers generated entangled photons using a device they designed to produce multiphoton entanglement of microwave light at frequencies near 5 GHz—the same frequency band as wireless communications used by cellphones and Wi-Fi connections.

Next, they created a classical source of photons that, on the surface, replicated the signals produced by the quantum device, but without the entanglement. When the photons from each source were sent through the detection scheme, in a head-to-head comparison between the quantum and classical protocols, the researchers found that the quantum source outperformed the classical source by a factor of 10.

They found that the improved performance occurred only when the signal levels were around the single-photon level, which is much weaker than what a typical radar system uses. While there are clear technical paths to improve the signal power, Wilson notes, “There is an enhancement when your signal power is inherently small, so this has potential applications in situations where the user doesn’t want the subject to know they are being tracked.”



Micrograph of the device used to generate the entangled microwave signals. The measured correlations between the signals that prove they are entangled. Cartoon of the radar protocol.

The experiment marked a milestone as the first demonstration of quantum illumination in the microwave regime. “This is exciting because it is the same frequency that most radar systems operate at, meaning there could be more immediate, practical applications for current radar technology,” explained Wilson.

It also shows the potential for quantum microwaves to have real-world applications outside of the cryostat at room temperature, an exciting prospect for Wilson:

“Understanding why this actually works could be a really important step in unlocking more applications for quantum microwaves.”

Quantum-Enhanced Noise Radar, in collaboration with the Université de Sherbrooke and Defence Research and Development Canada (DRDC), appeared as the cover article of Applied Physics Letters on March 18. This research has been undertaken in part thanks to the Canada First Excellence Research Fund (CFREF).

Continue to publish research results in world-leading journals

Publications and Citations

As IQC researchers continue to advance the field of quantum Information science and technology, publications and citations become important indicators of scholarly impact as they help to measure research output and intensity. In 2018-19, IQC’s collective research community published 136 papers.

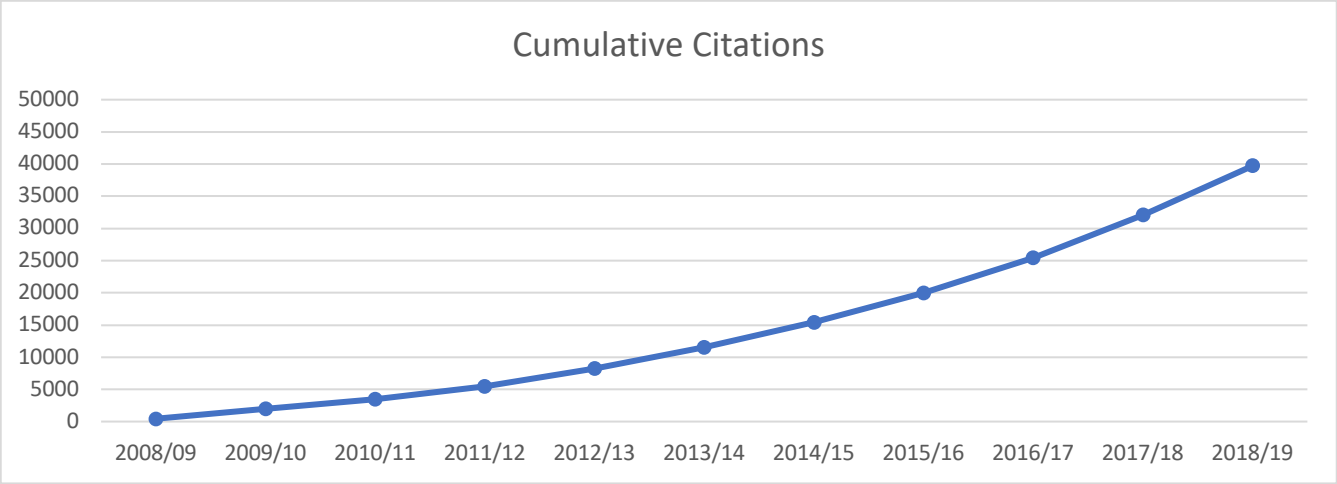
70% of all co-authored papers (from 2002 through to the present) have been published with international collaborators from leading universities and institutes including Massachusetts Institute of Technology (MIT), Tsinghua University, Harvard, University of British Columbia and Université de Sherbrooke.

IQC’s scientific achievements are further strengthened when considering the number of prominent journals where researchers have published. The chart below indicates the number of high-level, peer-reviewed discoveries since 2012 – IQC researchers have published 198 papers in these high-ranking journals.

Publication	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
Nature	1	1		2	1		2	
Nature Photonics	1		3	2	1	2		
Nature Physics	3	2	3		2	1	1	
Nature Communications	1	1	1	5	3	4	3	4
Physical Review Letters	17	14	14	16	17	11	6	8
Science	2	1	1	3				1
Journal of Mathematical Physics	4	6	4	4	6	2	3	3
FOCS	1	1			1			
STOC							1	1

A full list of all papers published in 2018-19 can be found in Appendix B on page 42.

Citations are another indicator of the strength of research published. As of the writing of this report, the number of cumulative citations from IQC's published papers reached 39,710. The growth chart below highlights the large increases in IQC citations given faculty growth, showing the high impact of IQC researchers.



Note: *Source for all publication information: Web of Science; Search: AD= ((Inst* Quant* Comp*) OR IQC) and ad = waterloo; timespan April 1, 2018 – March 31, 2019. Data pulled as of March 31, 2019.*

Recruiting New Researchers

Faculty

IQC is currently home to 30 full-time faculty members and continues to have a high faculty retention rate. In the past two years, IQC has welcomed nine new faculty, including David Gosset in this past year:

David Gosset joined the Institute for Quantum Computing (IQC) as an Associate Professor in the Department of Combinatorics and Optimization at the University of Waterloo on August 1, 2018.

Gosset received his PhD in Physics from MIT in 2011 under the supervision of Edward Farhi. His doctoral work focused on the power and limitations of quantum adiabatic algorithms. This spurred his interest in the computer science perspective on physics and its application to models of computation, the computational complexity of quantum many-body systems, and quantum algorithms.

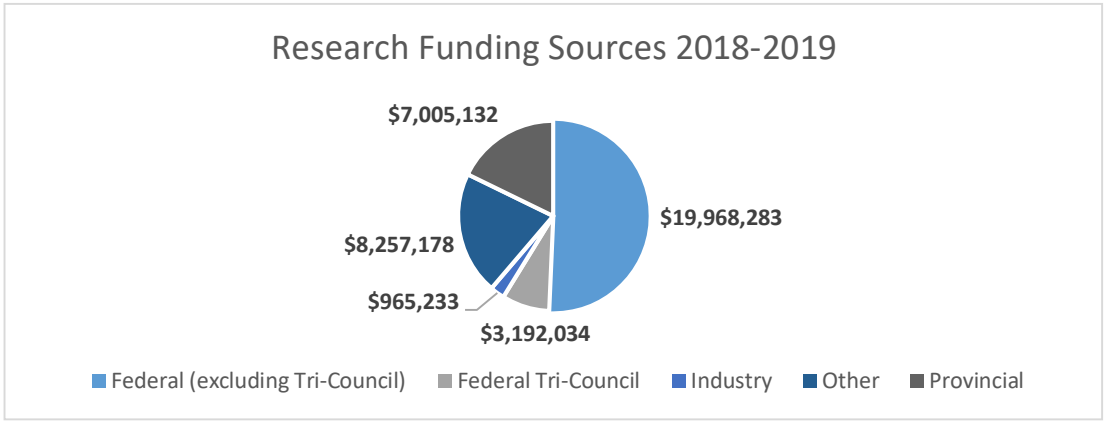
He subsequently held postdoctoral fellowships at IQC and at Caltech, before joining the IBM T.J. Watson Research Center in 2016.

Gosset's research at IBM focused on fundamental questions in quantum algorithms and complexity theory which are guided by the impending availability of small quantum computers. He was most recently managing the Theory of Quantum Algorithms group at IBM, before returning to IQC.

At the current growth rate, it is estimated that IQC will reach its target 39 faculty by 2023. A full list of all 30 current faculty members can be found in Appendix C on page 48.

Research Grants

In this fiscal year, IQC's research income totaled $39.3M from federal sources, federal tri-council programs, provincial programs and industry. This is an increase of over $6M in research funding over and above last year's total in the same categories. This 16% overall increase derives from increases in each of the funding categories. While sources of funding from within the Province of Ontario accounted for the single highest dollar increase of any category ($968,974), the largest percentage increase was 445% and came directly from industry sources. A high-level summary of funding sources from this fiscal year is illustrated in the following graph:



Note: *The information provided above outlining Research Grants is calculated based on the University of Waterloo's fiscal year. This data represents May 1 2018 through April 30, 2019.*

Faculty Awards and Chairs

Awards granted to faculty are a testament to the high calibre work being conducted at IQC. They are recognition of research excellence and impact by the scientific community. In a globally competitive environment, such indicators are critical because when it comes to research, established success is what attracts new resources.

Below is a list of awards faculty members received in 2018-2019.

Faculty Member	Award	Source
Michal Bajcsy	Free-space polarization-selective microcavity based on chiral meta-surfaces	Canada First Research Excellence Fund, TQT-QQSF
	Hybrid Quantum Repeater based on Atomic Quantum Memories and Telecom Wavelength Entangled Photon-Pairs Generated from Semiconductor Nanowires	Canada First Research Excellence Fund, TQT-QQSF
	On-Chip Microwave-Optical Interface	Canada First Research Excellence Fund, TQT-QQSF
	Quantum Light Sources Based on Deterministic Photon Subtraction	Canada First Research Excellence Fund, TQT-QQSF
	Chiral Quantum Antenna Based on Multilayer Metasurface	Canada First Research Excellence Fund, TQT-QQSF
Jonathan Baugh	WIN Research Leader Award	Waterloo Institute for Nanotechnology
	NSERC Discovery	Natural Sciences and Engineering Research Council of Canada
Kyung Soo Choi	KIST Open Research Program	Korean Institute of Science and Technology
David Gosset	IBM US research grant	IBM USA
K. Rajibul Islam	NSERC-Discovery	Natural Sciences and Engineering Research Council of Canada
	TQT Grand challenge (CFREF)	Transformative Quantum Technologies
Thomas Jennewein	Wilhelm Exner Medal	Austrian Industry Association
Adrian Lupascu	University of Waterloo	Waterloo-Technion cooperation
Norbert Lütkenhaus	NSERC - CRD	Natural Sciences and Engineering Research Council of Canada
Michele Mosca	Security and Anti-Fraud Innovation Award	Webit
	Knight in the order of Merit of the Italian Republic	Italian Republic
	Development of new quantum circuits for simulating the electronic structure of OLED materials	Natural Sciences and Engineering Research Council of Canada
	Post Quantum Cryptography Analysis	Government of Canada
	Quantum Key Distribution	National Research Council

Faculty Member	Award	Source
	A Secure Scalable Quantum-Safe Blockchain for Critical Infrastructure	National Research Council - UW Collaboration Centre for AI/Cybersecurity/IoT
	Cybersecurity, Privacy, and International Affairs	Cybersecurity Privacy Institute
Christine Muschik	Alfred P. Sloan Research Fellowship	Alfred P. Sloan Foundation
Dmitry Pushin	NSERC Discovery grant	Natural Sciences and Engineering Research Council of Canada
	2018 Science Prize of the Neutron Scattering Society of America	The Neutron Scattering Society of America
Kevin Resch	Innovation, Science & Economic Development	Government of Canada
	Tier 2 Canada Research Chair	Canada Research Chair in Optical Quantum Technologies
Crystal Senko	NSERC Discovery	Natural Sciences and Engineering Research Council of Canada
	TQT Grand Challenge (CFREF)	Transformative Quantum Technologies
William Solfstra	NSERC Discovery	Natural Sciences and Engineering Research Council of Canada
Wei Tsen	Transformative Quantum Technologies Quantum Seed Round 4	Canada First Research Excellence Fund
	UW-POSTECH collaboration on wafer-scale 2D magnetic heterostructures for next-generation spintronic devices	University of Waterloo International Research Partnership Grant
	Early Researcher Award	Ontario Ministry of Research, Innovation, and Science
	Waterloo Institute for Nanotechnology Research Leader Award	Waterloo Institute for Nanotechnology
John Watrous	Canadian Institute for Advanced Research Grant	Canadian Institute for Advanced Research
Christopher Wilson	Novel Qubit Designs	Anyon Systems Inc.
	Microwave Quantum Radar	Defense Research & Development Canada
	Fabrication Techniques for High-Coherence Superconducting Qubits	NSERC - Engage
Jon Yard	NSERC Discovery	Natural Sciences and Engineering Research Council of Canada

Note: *due to the internal reporting structure, it is possible there are additional awards not captured in this chart. Please see Research Grants on page 20 for total incoming research dollars in this reporting period.*

Current Research Chairs

Externally funded research chairs, including the Canada Research Chairs and chairs supported by funding from other external organizations, reflect the performance and success of IQC researchers. Internal research chairs, or University Research Chairs, recognize exceptional achievement and pre-eminence in a particular field of knowledge.

The following IQC faculty members hold external or internal chair awards:

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

Continue to outfit labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre as new IQC members are recruited

There are 14 operational research labs in the Lazaridis Centre, with additional labs currently being designed for experiments by IQC's recently recruited faculty members.

Active research labs in the Lazaridis Centre (QNC) include:

Quantum Photonics Laboratory
Satellite Quantum Key Distribution Laboratory
Integrated Quantum Optoelectronics Laboratory
Quantum Verification Laboratory
Laboratory for Digital Quantum Matter
Quantum Optics and Quantum Information Group Laboratory
Engineered Quantum Systems Laboratory
Integrated Nano Electronics
Ultracold Quantum Matter and Light

Each lab is maintained and updated by respective researchers. Two of the more recent experimentalists to join IQC – Rajibul K. Islam and Crystal Senko – are still in the process of acquiring equipment for their labs.

In the past year, Islam continued progress in his lab by acquiring two class 3b diode laser systems and with additional bulk orders of optics and opto-mechanics equipment. His research group has begun building optics layouts for experiments with trapped ions, and he is consistently acquiring and stocking up on optics equipment.

Crystal Senko, who also joined IQC as a faculty member in the fall of 2016, is in the final stages of constructing an apparatus for trapping, manipulating and measuring the electronic states of charged particles (ions). This includes ion trap electrodes that will be housed in an ultra-high vacuum chamber; circuits to provide the voltages to trap the ions; modulated diode lasers that will be used to cool the ions once they are trapped; and other lasers used to produce ions to trap and control electronics to handle the timing of various instruments.

Continue to outfit and maintain the Quantum NanoFab facility to enable fabrication of quantum-enabled technologies

This past year, the Quantum NanoFab Facility underwent a transformation in name and reporting structure. Now reporting directly to the University of Waterloo's Office of Research, the renamed Quantum-Nano Fabrication and Characterization Facility (QNFCF) assumed responsibility for three labs in the Quantum Nano Centre's Metrology area: TEM lab, FIB lab and Dry Sample Prep lab. New equipment and upgrades to the QNFCF, totalling $263,792, were funded by IQC.

In early June, the QNFCF team further expanded their team to include the role of Nanofabrication and Characterization Scientist. Sandra Gibson, who earned her PhD in Engineering Physics at McMaster University, recently completed an appointment as a Postdoctoral Fellow in Michael Reimer's group at IQC. This position is supported by IQC and the CFREF-TQT program.

Each year, new members are trained, including third part companies who require access to technology housed within the QNFCF. Over 2018-2019, demand for the QNFCF grew by 50%.

Update and maintain lab space in Research Advancement Centre (RAC) buildings

IQC's QNFCF team took delivery of a new Chemical Vapour Deposition (CVD) system which will be used for growing Carbon Nanotubes in support of multiple quantum research projects. This system has been installed in RAC2 and will be operated through the Quantum-Nano Fabrication and Characterization Facility team. Further improvements to RAC2 labs have included the installation of a waterjet, and a 20 Tesla magnet and dilution refrigerator.

Meanwhile in RAC1, renovations are underway to create a Quantum Explorations Space. This space will be used to give students and visitors access to real research-grade quantum systems for laboratory experiments and knowledge building. The space will allow students in programs such as USEQIP and QCSYS to get detailed hands-on experience with real systems, and allow large numbers of industry experts and visitors to see real quantum devices in action.

Continue effective and relevant relationships with current partners. Seek out new partnerships that will advance IQC's mission and strategic objectives.

Collaboration has always been at the core of IQC's research success. IQC's ongoing research partnerships span the globe, encompassing collaborations with other universities as well as

non-profits, government and private organizations. These partnerships drive innovation and position IQC as a key player in the innovation economy.

In 2018-2019, IQC's researchers reported 53 ongoing collaborations with 53 unique organizations. Appendix D, on page 49 lists current collaborations by faculty member.

Note: due to the University of Waterloo's Intellectual Property Policy (Policy #73) faculty are not required to report all external relationships. The actual number of current collaborations could be higher than reported.

Seeking New Strategic Partnerships

As strengthening the bridge between science and commercialization is a high priority for IQC's researchers and administration, efforts to establish new and maintain existing strategic partnerships is of the utmost importance year-round. Below are select highlights of initiatives taken by IQC staff and researchers over the past year:

- In April 2018, it was announced that Canada's Department of National Defence was investing $2.7 million into an IQC-led project to develop technology for quantum radar. The technology will aim to help radar operators cut through heavy background noise and isolate objects —including stealth aircraft and missiles— with unparalleled accuracy. Faculty member Jonathan Baugh is leading the project along with three other researchers from IQC and the Waterloo Institute for Nanotechnology.

- In the fall, IQC administrative staff facilitated day-long visits from potential investors and industry partners including representatives from Google, IBM, Alibaba and Rank Group Limited. All faculty members were invited to participate in meetings with these groups.

- Attending third party conferences that are focused on the convergence of quantum and industry has also become a key strategy to seek new partners this year. Details of attendance at these conferences can be found on page 55.

Objective B

Create new opportunities for students to learn and 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 2018-2019

- 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

Progress Achieved for 2018-2019

Attracting Talent and Connections to IQC

Each year, programs such as the Undergraduate School for Experimental Quantum Information Processing (USEQIP) attract the best and brightest undergraduate students from around the world to consider IQC for graduate school. In 2018-2019, 288 undergraduate students applied to either USEQIP or USEQIP and an Undergraduate Researcher Award (URA). An additional 98 students applied for only a URA. A total of 21 students from the top institutions worldwide, including Massachusetts Institute of Technology, the India Institute for Technology and the University of Toronto were among those awarded an Undergraduate Researcher Award. An additional 38 research assistants were hired for research work terms directly by faculty members. 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.

Attracting the highest calibre researchers and developing talent remains a top priority for IQC. The chart below summarizes all incoming highly qualified personnel over the last year.

HQP	Ontario	Other Provinces	Outside Canada	Unknown	Total Reporting Period	Current Total
Faculty + RAPs	-	-	1	-	1	32
Postdoctoral Fellows	4	1	20	-	25	48
Doctoral Students	-	-	16	1	17	89
Masters Students	13	1	11	-	25	85
Undergraduate/ Equivalent (URAs)	-	-	-		38/21	27
Total						**282**

Postdoctoral Fellows

Postdoctoral fellows are early career scientists with experience and innovative approaches to quantum research. Fellowship positions provide young scientists opportunity for additional mentoring, to publish their work and for research and teaching experience.

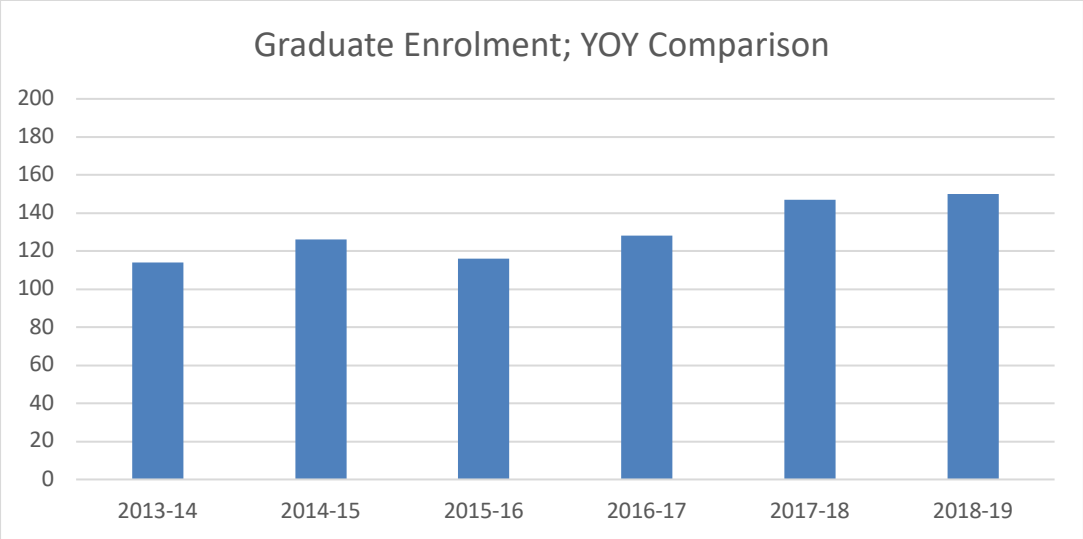
2018-19 was a hugely successful year for IQC in terms of postdoctoral recruitment. Over the fiscal year, IQC welcomed 25 new postdoctoral fellows, far exceeding the goal of five and representing a 38.89% increase in recruitment from last year.

The current total of postdoctoral fellows to 48. Of the 48, 10 (20.83%) are female and 38 (79.17%) are male. The 25 new fellows came to IQC from some of the top institutions in the world, as shown in the table below. A full list of current postdoctoral fellows can be found in Appendix E on page 51.

Canada	USA	International
University of Waterloo	Penn State University	National University of Singapore
University of Toronto	University of Maryland	University of Bern
Université de Sherbrooke	Florida Atlantic University	Indian Institute of Science
		Aalto University
		Shanxi University
		Tianjin University
		University of Bristol
		Universita Degli Studi Roma Tor Vergata
		Aarhaus University
		Paris-Sud University
		University of Copenhagen
		Ulm University

Students

IQC welcomed 41 new graduate students this past year from 268 applications, bringing the total number of Master's and PhD students to 197 (98 and 99, respectively) throughout the fiscal year. The current total as of March 31, 2019 is 173 graduate students (84 Master's and 89 PhD).



A full list of graduate students as of March 31 2019 can be found in Appendix F on page 52.

Student Awards

This year, IQC graduate students were collectively awarded over 169 separate awards. These awards are testament to the students' research excellence and provide the funding needed to allow students to devote themselves to their studies.

Of the 169 awards to 116 individual students, 33 (19.5%) were presented to 21 (18.1%) individual female students.

Awards earned by IQC graduate students in this year include:

- 13 M&O Lazaridis Fellowship
- 2 IQC Entrance Award
- 36 International Doctoral Student Award
- 39 International Masters Student Award
- 1 IQC Achievement Award
- 2 IQC David Johnston Award for Scientific Outreach
- 6 NSERC Alexander Graham Bell Canada Graduate Scholarship - Doctoral
- 10 NSERC Alexander Graham Bell Canada Graduate Scholarship - Masters

- 7 NSERC Postgraduate Scholarship - Doctoral
- 5 NSERC Vanier Canada Graduate Scholarship
- 9 Ontario Graduate Scholarship
- 33 President's Graduate Scholarship
- 2 Provost Doctoral Entrance Award for Women
- 1 Ontario Trillium Scholarship
- 3 QEII-Graduate Scholarship in Science and Technology

Expand connections made with undergraduate programs at Ontario and Canadian universities

IQC's Manager, Scientific Outreach was invited to give five talks to undergraduate students at Maritime universities. The talks, organized by the Canadian Association of Physicists, was on the Second Quantum Revolution and took place as follows:

- Memorial University of Newfoundland, St John's, NL, February 25, approx. 25 students
- Dalhousie University, Halifax, NS, February 26, approx. 60 students
- Université de Moncton, Moncton, NB, February 27, approx. 20 students
- Mount Allison University, Sackville, NB, February 28, approx. 30 students
- UPEI, Charlottetown, PEI, Mar 1, approx. 30 students

To round off the tour, IQC presented the talk to an audience of approximately 20 undergraduate students at the University of Windsor, ON.

Movement of HQP

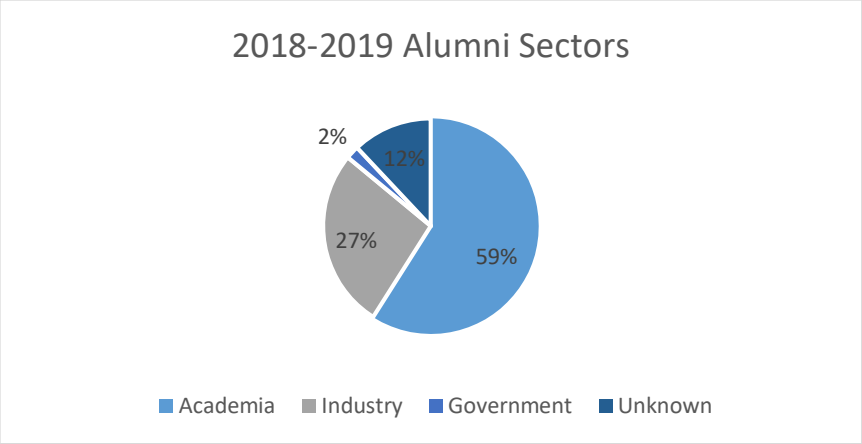
Throughout the course of the year, IQC members completed degrees and successfully moved into advanced programs, postdoctoral fellowships, faculty positions or careers in industry. The table below summarizes the highly qualified personnel (HQP) who left IQC within the last year.

Location	Inside Ontario	Outside Ontario	Location Unknown	Total
With private sector firms	2	1	-	3
At publicly funded research institutions/universities	7	-	-	7
With government of NFP groups	-	1	-	1
Other	-	-	-	-
Unknown	-	1	6	6
Total	9	3	6	18

Alumni

Alumni success is an important indicator of program quality and student success. This fiscal year, a total of 18 students graduated – eight with PhDs and ten Master's students - bringing the number of IQC student graduates to 215 cumulatively. These researchers have chosen to go into various fields, from academia to government to industry, both within Ontario and around the world. Four of this year's 18 graduates were female: two moved onto technology-related employment and one stayed in academia (the destination of one is unknown).

The chart below indicates the distribution of IQC alumni. Specifically, 59% of IQC graduates stayed in academia, with 27% and 2% moving to industry and government, respectively.



Continue to host timely, focused 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, two workshops, 43 seminars and 21 colloquia, and jointly sponsored an additional 11 conferences and workshops held at partner organizations across the globe. Below are highlights of major conferences hosted and sponsored this year.

Major Conferences

In 2018-2019, IQC hosted three major conferences for attendees from around the world, details of which are on page 32.

In addition to hosting these conferences, IQC faculty collectively were invited to speak at over 114 other conferences around the world this year. A full list of faculty-attended conferences and invited talks can be found in Appendix G on page 55.

Workshops

Two workshops were hosted by IQC this fiscal year. From July 5-6, **Security Proofs in Quantum Key Distribution (QKD)** brought together experts in the security analysis of QKD to discuss different approaches of security analysis and aspects such as finite size effects, reduction of assumptions and tightness of rates. In late November, IQC hosted its annual high school teacher workshop, **Schrödinger's Class**, for 39 educators from across North America. Participants attended lectures and engaged in hands-on activities focused on the integration of quantum technology into the current teaching curriculum.

Seminars and 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 43 seminars and 21 colloquia. Appendix H on page 62 has a full list from this year.

Sponsored Conferences

Each year, IQC commits to supporting external conferences and workshops to encourage opportunity for collaboration among a global network of researchers. This year, IQC sponsored 11 external events which are listed in the chart below

Date	Conference	Location
May 24-26	Spin Canada	University of Calgary
June 3-7	Quantum Physics & Logic	Dalhousie University
June 7-9	Theory Canada 13	St Francis Xavier University
June 7	Many-body States & Dynamics Workshop	IQC / Perimeter Institute
July 23-27	Security Proofs in Quantum Key Distribution	IQC
July 17-20	Women in Physics Canada	Université de Sherbrooke
August 15-18	Canadian Undergraduate Physics Conference	University of Alberta
October 2-6	IQC-China Conference on Quantum Technologies	IQC
October 22-26	Q-Turn: Changing Paradigms in Science	Universidade Federal de Santa Catarina
January 14-18	Quantum Information Processing	University of Colorado, Boulder
January 18-20	Canadian Conference for Undergraduate Women in Physics	University of Ottawa

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.

- Be a catalyst for collaborations of quantum information scientists across Canada and the world
- Promote collaborations through participation in national and international conferences
- Produce internationally recognized, high-calibre publications co-authored by IQC researchers
- Organize at least four conferences that involve multidisciplinary participants
- Continue, enhance and increase visits to IQC by international scientists and academics

Progress Achieved for 2018-2019

Be a catalyst for collaborations of quantum information scientists

IQC faculty member Debbie Leung participated in a panel on building quantum computers at the American Association for the Advancement of Science (AAAS) Annual Meeting, which took place in Washington, D.C. in February. Leung's talk explored how the speed-up of computational problems using quantum mechanics relies on accurate control of the quantum system through a vast and fragile state space. She examined the level of precision and resources required to achieve large scale quantum computation, why this should be feasible, what had been demonstrated so far, what obstacles lay ahead, and how optimistic we should be.

Promote collaborations through participation in national and international conferences

Attending third party conferences that are focused on the convergence of quantum and industry has become a key strategy to seek new partners this year.

- In mid-September IQC sent representation to the annual AI Summit in San Francisco. This summit had a quantum stream and hosted 4,000 delegates, primarily from industry. Professor Na Young Kim was given a speaking opportunity and addressed an audience on IQC and its model. Members of the IQC communications team staffed a booth for the duration of the event.
- In October, the Hudson Institute in Washington, D.C. hosted a day-long summit entitled Canada's Quantum Valley: An Integrated Pathway to the High-Tech Future, attracting an audience of approximately 100 participants. IQC faculty members Raymond Laflamme and Joseph Emerson were among the speakers that discussed the ecosystem clustered around the University of Waterloo.
- In November, IQC attended the Canadian Science Policy Conference and hosted a panel to explore how Waterloo's unique innovation ecosystem is distinguished by its inventor-owned IP policy, entrepreneurship programs, business incubators

and robust industry partnerships. IQC researcher Kristine Boone participated in the panel sharing her perspective as both a PhD student and as a quantum entrepreneur.

- Also in November, Tracey Forrest (Program Manager, Transformative Quantum Technologies) attended the UK's National Quantum Technologies Showcase in London. This event demonstrated progress from the UK's National Quantum Technologies Research Programme, its relevance to commercial sectors and the collaborative nature of the programme involving academia, industry and government partners.
- In December, IQC attended the second annual Quantum for Business conference hosted in Mountain View, California and staffed a booth on the tradeshow floor. IQC postdoctoral fellow and entrepreneur, Vlad Gheorghiu, gave a talk entitled: Quantum Threat: What Matters Today?
- In March, IQC staff attended Inside Quantum Technology's inaugural conference in Boston. In addition to staffing a booth at this conference, two of IQC's faculty members – Joseph Emerson and Michele Mosca – spoke as part of panel discussions and Joseph presented a keynote lecture. Inside Quantum Technology focused on the future on quantum computing, quantum cryptography and quantum sensors and was intended to explore opportunities available to industry and government.

Appendix G on page 55 provides a full list of all these other international conferences attended by faculty members this year.

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

Researchers at IQC regularly collaborate with other researchers and scientists around the world in an effort to create scientific networks that produce the highest standard of research. 70% of all IQC papers are co-authored with researchers outside of Canada. For a list of the 136 papers published this year, see Appendix B on page 42. A list of active collaborations by researcher can be found in Appendix D on page 49.

Organize at least four conferences that involve multidisciplinary participants

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

- **IQC-China Conference on Quantum Technologies**, October 2-6
  - This conference brought together approximately 60 scientists from China and Canada to nourish more extensive collaborations and to educate younger generations.
- **Quantum Innovators: Science and Engineering**, October 15-18
  - Held at IQC the Quantum Innovators in Science and Engineering workshop brought together the most promising young researchers in quantum physics and engineering.
- **Quantum Innovators: Computer Science & Mathematics,** October 22-25
  - The second annual Quantum Innovators in Computer Science and Mathematics 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.

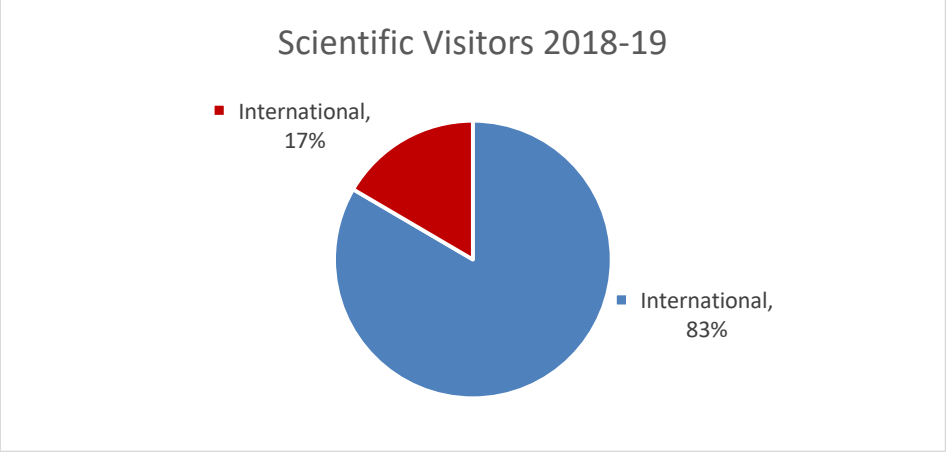
Continue, enhance and increase visits to IQC by international scientists and academics from around the world

Scientific Visitors

Every year, IQC's faculty and students host scientific 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. This year, IQC researchers collectively hosted 157 visits representing 149 unique scientific visitors from 122 unique organizations.

IQC's global reach is truly impressive with visitors coming from all across the world including: the United States (University of Colorado, Boulder, Massachusetts Institute of Technology, Stanford University, Princeton University) and from the world (Tsinghua University, Technology University - Delft, University of Cambridge, University of Innsbruck, University of Sydney). In 2018-2019, 83% of scientific visitors were international.

Nationally, IQC continues to strengthen its relationships with other Canadian universities and organizations in quantum information science and technology. This year IQC hosted Canadian visitors from a range of institutions including: University of British Columbia, University of Manitoba, University of Alberta, and Université de Sherbrooke. A full list of scientific visitors can be found in in Appendix I on page 65.



Tours and visitors

Hosting meetings and tours for industry, academia and government remains a key component of IQC's advancement activities. In 2018-2019, IQC received a large number of requests to visit, tour facilities, meet researchers and learn more about the Institute, its work, and potential opportunities for investment, partnerships and educational development. More specifically, over the past year, IQC faculty and staff welcomed over 440 visitors to the Institute. A full list of tours can be found in Appendix J on page 70.

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.

- Host USEQIP (undergraduate) and QCSYS (high school) summer schools
- Host the fourth annual high school teacher's workshop
- Host public lectures
- Host QUANTUM: The Exhibition in Toronto's Ontario Science Centre
- Continue to leverage the quantum pop-up exhibit
- Establish relationships with key strategic partners to further share IQC's research discoveries

Progress Achieved in 2018-2019

Host major undergraduate and high school summer schools

USEQIP

From May 28 to June 8, IQC hosted its annual Undergraduate School for Experimental Quantum Information Processing (USEQIP).

Out of 288 applications, 16 female and 15 male students were selected for the program that explores theoretical and experimental quantum information. This means that for every nine applications, only one student was selected.

Participants came from across Canada, the United States, India, the United Kingdom, France, Greece, Germany, Russia, Serbia, Spain, Chile, Mexico and China.

"USEQIP was an absolutely amazing experience. Not only were the lectures and labs engaging, it was the best chance to spend time with other top students from around the world. The curiosity that everyone showed – from us undergrads to the tenured professors – really excited me for seeing a quantum revolution in our near future." USEQIP 2018

In a survey of the students following the summer school, 100% of the students agreed or strongly agreed that the program gave them the tools needed to begin investigating the quantum information field and 89.5% reported they would actively encourage others to apply to

USEQIP. 91% of respondents agreed or strongly agreed with the statement, *"The things I learned in USEQIP, I could not have learned anywhere else in my undergraduate studies."*

QCSYS

From August 10 to 17, IQC hosted its annual Quantum Computing School for Young Students (QCSYS). IQC received 242 applications from high school students around the world and invited 44 participants to Waterloo to get a first-hand look into the physics and mathematics of quantum mechanics, cryptography and how they merge into one of the most exciting topics in contemporary science – quantum cryptography. This translates to one student being accepted for every five applications. Of the 44 students accepted, 22 were female and 22 were male. Collectively, they represented Canada, the US, Greece, India, Bangladesh, Poland, Singapore and the UK.

In a survey of the students following the summer school, 100% of respondents rated the program as excellent (88%) or good (12%). 100% of respondents agreed (50%) or strongly agreed (50%) with the statement, "QCSYS enticed me to look into what I would need to pursue a future in quantum information science", while 94% strongly agreed and 6% agreed with the statement, "QCSYS exposed me to ideas not available in my high school classes".

Applications are already in for 2019's QCSYS and overall have increased by 21.7%, with a 26% increase in applications from female students specifically.

Host the fourth annual high school teacher's workshop

Schrödinger's Class

From November 30 through December 2, IQC hosted its fourth annual high school teacher workshop, Schrödinger's Class. After receiving 91 applications from teachers across Canada and the United States, a total of forty invitations were sent. Thirty-nine teachers – 20 male and 19 female – 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 beyond the basics 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.

Host public lectures

Last year, IQC established a new series of public lectures called *Entangled: The Series.* On April 26, IQC hosted its first *Entangled* event of the year. The talk, *Quantum Fiction: The Entanglement of Physics and Literature,* was presented by Chad Orzel, author and professor at Union College. Orzel's talk described some of the strangest phenomena in quantum mechanics - topics like entanglement, quantum measurement, and Schrödinger's infamous cat - followed by a discussion of how they have been manifested in literature and film. Following this lecture, Orzel was also invited to write about his body of work in an article for Forbes Magazine.

The second *Entangled* talk of the year, held in September, featured IQC alumnus Chris Ferrie

who discussed *Quantum and Opportunity.* This talk was a historical journey of the speaker's own coming of age with digital software. Chris explained one of the main lessons he learned from his journey was that children will take advantage of the opportunities they are given, but only if their parents and teachers show genuine interest in the activities giving rise to those opportunities.

IQC then partnered with the Royal Canadian Institute for Science (RCI) on two public lectures as part of the *Entangled* series. On November 1, Martin Laforest presented *Quantum + Beer* at the Patent Social in Waterloo and on November 15, John Donohue presented *Quantum + Pop Culture a*t IQC. Each talk had an audience of approximately 70 people.

Host QUANTUM: The Exhibition in Toronto's Ontario Science Centre

In late August, IQC installed and opened the quantum exhibition in its seventh location, the Ontario Science Centre in Toronto. The exhibition was on display until January 6 and was viewed by over 294,000 visitors. In October, IQC worked with Science Centre staff to host custom programs in Toronto promoting awareness of quantum science and information technology.

Continue to leverage the quantum pop-up exhibit

From October 2018-February 2019, QUANTUM: The Pop-Up Exhibit was on display at the Saskatchewan Science Centre in Regina and viewed by 14,500.

With February 11 being the International Day for Women and Girls in Science, IQC outreach staff took the opportunity to partner with the Science Centre on a joint event for girls in Saskatchewan. IQC researchers, Julia Maristany and Nairong Hou, were two of five female panellists that presented to a group of 100 local high school students. The panel focused on careers and obstacles for women in STEM fields.

Establish relationships with key strategic partners to further share IQC's research discoveries

New partnerships with scientific outreach groups present themselves regularly. This year, IQC attended NSERC's annual Canada Wide Science Fair for the first time and presented the quantum pop-up exhibition. This event, which is part of the national initiative Science Odyssey, drew approximately 10,000 students from across Canada. IQC plans to continue this relationship by attending future events.

As mentioned above, IQC was also able to forge a new partnership with the Royal Canadian Institute for Science (RCI). RCI's goal is to provide public access to talks from a wide spectrum of scientific disciplines and IQC was pleased to take advantage of the opportunity to partner with the RCI on the *Entangled* series. IQC's outreach team intends to grow this relationship to reach more people each year.

Continue to share IQC's research through publications, web and social media outlets

Communications

The communications team at IQC ensures that the researchers and their work are recognized worldwide through publications, media releases and online platforms.

Publications

This year IQC was pleased to accept two awards for its work on the 2017 IQC Annual Report. This special 15th anniversary edition received a 2018 Award for Publication Excellence (APEX). APEX 2018 awards were based on excellence in graphic design, editorial content and the success of the entry – in the opinion of the judges – in achieving overall communications effectiveness and excellence. Of 1,408 entries, 41 annual reports received an award. In addition, it received a 2019 Gold CASE Accolades Award for "Annual or Institutional Reports: Print" category.

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 1286 media mentions of IQC were recorded which translates to a reach of 488,297,629 impressions (the number of times that a post has been viewed on a feed).

Social Media

Throughout last year IQC has enjoyed steady growth across all its social media platforms. Below are some highlights of social platform growth from April 1, 2018 to March 31, 2019.

	New Followers	Total Current Followers	Increase
YouTube	873	5,196	20%
Facebook	2,539	14,703	21%
Twitter	1,315	12,098	12%
Instagram	120	653	23%

Consistent online growth is a positive sign that points toward IQC's established position of being an authoritative voice in its field. As a testament to IQC's thought leadership in quantum information, take the following examples from the past year:

- An existing video on the IQC YouTube channel - "Steven Girvin – Quantum Hall Effect" – enjoyed a significant spike in views in winter 2018. Upon researching the reason for this spike, IQC found that it directly followed a paper published by an external researcher on the same topic. It seems online subscribers appeared to look to IQC to learn more on the subject. IQC's video was shared 271 times and accounted for more than a third of the most shared videos during the first quarter of the year. IQC's YouTube channel also enjoyed an increase of 86 subscribers in that short time alone.

- IQC also tested a new initiative on social media last year that involved leveraging the mainstream popularity of the "quantum realm" as depicted in *Ant-Man and the Wasp* (released July 2018). The film's release provided an opportunity to connect with and reach one of IQC's "unaudiences" – moviegoers and superhero enthusiasts – who otherwise may not know about quantum science. The goal of the campaign was to engage and build awareness of quantum among moviegoers by sharing social cards, relevant YouTube content, and IQC's "Quantum Toolbox" webpage through social media platforms. With a small investment in paid social advertising, the campaign, which consisted of only 11 tweets and 5 Facebook posts throughout July, resulted in:

    - 20,258 impressions on Twitter, 149 new followers
    - 14,880 reach on Facebook, 103 new likes
    - Website traffic to Quantum Computing 101 with an average time on page 05:52, well over the industry benchmark of 02:31
    - Combined YouTube watch time of 283 minutes, spike in watch time, and 181 new subscribers

These examples speak to IQC's status as an authoritative voice in the area of quantum information and give insight to how users rely on the information provided here.

Objective E

Increasingly translate research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada.

Expected Results: Position Canada to take advantage of economic and social benefits of research through seizing opportunities to commercialize breakthrough research.

Planned Activities 2018-2019

- Continue development of an industry affiliate program
- Promote opportunities for IQC researchers to connect with Waterloo's entrepreneurial ecosystem through networking and formal events in partnership with the broader startup networks in Waterloo Region

Progress Achieved 2018-2019

IQC is a key player in the quantum science, technology and innovation ecosystem by continuing to create an environment that fosters entrepreneurship and supports the commercialization of quantum technologies.

As of March 2019, IQC faculty collectively hold over 44 granted patents and 30 licenses, including three new patents granted in 2018-2019. Currently, IQC faculty have 50 patent applications pending approval.

IQC spin offs have also grown over the past year. To date, the following fourteen companies have emerged as a result of IQC research, all of which are in the field of quantum information:

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

Note: *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.*

APPENDICES

A. Risk Assessment & Mitigation Strategies

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

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
IQC may not be able to attract high quality researchers	High	Medium	8	The market for world-class researchers is increasingly competitive with many countries making significant investments.	Pursue recruits from a wide breadth of areas of research. Offer competitive job offers/ package. Adequately promote the world-class researchers and the cutting-edge facilities/ equipment at IQC. Further invest in cutting edge laboratory facilities.
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 are 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.

B. Publications

April 1, 2018-March 31, 2019

1. Ahmadzadegan, A., & Kempf, A. (2018). On the Unruh effect, trajectories and information. Classical and Quantum Gravity, 35(18).
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C. Faculty Members and Research Assistant Professors

Faculty Members

Michael Bajcsy
Jonathan Baugh
Raffi Budakian
Kyung Soo Choi
David Cory
Richard Cleve
David Gosset
Joseph Emerson
K. Rajibul Islam
Thomas Jennewein
Na Young Kim
Raymond Laflamme
Debbie Leung
Adrian Lupascu
Norbert Lütkenhaus
Matteo Mariantoni
Gui-Xing Miao
Michele Mosca
Christine Muschik
Ashwin Nayak
Vern Paulsen
Dmitry Pushin
Michael Reimer
Kevin Resch
Crystal Senko
William Slofstra
Adam Wei Tsen
John Watrous
Christopher Wilson
Jon Yard

Research Assistant Professors

Francois Sfigakis
Joel Wallman

D. Collaborations

Collaborative Research Networks

Thomas Jennewein	Excelitas (former Perkin Elmer), Canada Canadian Space Agency, Montreal, Canada National Institute of Optics (INO), Canada DotFAST, Germany Princeton Lightwave, USA Xiphos, Montreal, Canada Neptec, Ottawa, Canada
Norbert Lütkenhaus	University of Vigo, Spain Technische Universitat Darmstadt, Germany Université Pierre et Marie Curie, France
Adrian Lupascu	IARPA and University of Southern California Milena Grifoni, Institute for Theoretical Physics University of Regensburg (Germany) Juan Jose Garcia Ripoll, the Institute for Fundamental Physics (Madrid) Qatar National Research Fund Jonathan Friedman, Amherst College, Massachusetts, USA
Michele Mosca	NSERC CREATE, Canada European Telecommunications Standards Institute, France Institute for Quantum Science and Technology (IQST), University of Calgary, Canada Université de Montréal, Canada Tech Capital Partners, Canada McGill University, Canada ComDev, Canada Perimeter Institute of Theoretical Physics, Canada National Institute of Standards and Technology (NIST), USA Swiss Federal institute of Technology in Zurich (ETHZ), Switzerland ID Quantique, Switzerland Institute for Security, Privacy and Information Assurance, Canada Centre for Quantum Technologies (CQT), NUS, Singapore Security Innovations, USA Tutte Institute for Mathematics and Computing, Canada Ontario Centres of Excellence, Canada MITACS, Canada Trustpoint, Canada SERENE, Canada

	Approach Infinity Inc., Canada University of Ottawa, Canada Government of Canada, Canada InfoSec Global, Canada SignitSure Inc, Canada
William Slofstra	Brown University, USA
Crystal Senko	Sandia National Labs
Christine Muschik	Karl Jansen - DESY Peter Zoller and Rainer Blatt - University of Innsbruck CDQI - Army Research Lab QTFLAG
Michal Bajcsy	Martin Houde from Western University Fetah Benabid from XLIM Research Institute in Limoges, France Philippe Tassin at Chalmer's University, Sweden
Guo-Xing Miao	Ambature, Inc., Scottsdale, Arizona
Chris Wilson	Professor Enrique Solano at the University of Basque Country, Bilbao, Spain Professor Ozgur Mustecaplioglu at Koc University in Istanbul, Turkey Professor Ivette Fuentes at University of Austria Dr. Jose Aumentado at NIST-Boulder

E. Postdoctoral Fellows

Current postdoctoral fellows at IQC:

Aaron Hutchinson
Aleksander Kubica
Anurag Anshu
Arjun Shetty
Behrooz Semnani
Ben Yager
Brendon Higgins
Chang Liu
Daniel Tennent
Dave Touchette
Divya Bharadwaj
Dmitry Akhmetzyanov
DongSheng Wang
Fereshteh Rajabi
Ferhat Aydinogluy
Franklin Cho
George Nichols
Geovandro Pereira
Hilary Carteret
Hyun Ho Kim
Ibrahim Nsanzineza
Jan Haase
Javad Doliskani
Jean-Philippe Bourgoin
Jinglei Zhang
Jinjin Du
Joachim Nsofini
John Peterson Pinheiro da Silva
Karthikeyan Sampath Kumar
Lin Tian
Long Cheng
Luca Dellantonio
Mahmood Sabooni
Mark Girard
Matthew Coudron
Matthew Day
Michele Piscitelli
Mohamad Niknam
Mona Mirzaeimoghri
Pan Zheng
Pardis Sahafi
Paulina Corona Ugalde
Pavithran Iyer
Peng Li
Peter Tysowski
Pooya Ronagh
Priyanka Mukhopadhyay
Roland Habluetzel
Sacha Schwarz
Salil Bedkihal
Sandra Gibson
Sangil Kwon
Sara Hosseini
Taehyun Yoon
Tian Lan
Travis Morrison
Vlad Gheorghiu
Wenfeng Li
Yasar Atas
Ying Dong
Yongchao Tang

F. Graduate Students

The IQC community included the following graduate students as of March 31, 2019.

PhD Students

Eugene Adjei
Arash Ahmadi
Rubayet Al Maruf
Matthew Amy
Vadiraj Ananthapadmanabha Rao
Paul Anderson
Shima Bab Hadiashar
Eduardo Barrera Ramirez
Stefanie Beale
Jeremy Bejanin
Marian Berek
Brandon Buonacorsi
Jamal Busnaina
Ningping Cao
Arnaud Carignan-Dugas
Poompong Chaiwongkhot
Xi Dai
Padraig Daly
Jack Davis
Jose de Ramon Rivera
Rahul Deshpande
Olivia Di Matteo
Carolyn Earnest
Jennifer Katherine Fernick
Jeremy Flannery
Thomas Fraser
Nicolas Funai
Kaveh Gharavi
Noah Greenberg
Daniel Grimmer
Holger Haas
Laura Henderson
Dmitri Iouchtchenko
Rabiul Islam
Aditya Jain
Jie Lin
Junan Lin
Sheng-Xiang Lin
Li Liu
Benjamin Lovitz
Jean-Philippe MacLean
Antonio Martinez
Caroline Mbakob- Tchouawou
Arthur Mehta
Maryam Mirkamali
Abel Molina
Sainath Motlakunta
Mike Nelson
Mohamad Niknam
Jean-Luc Orgiazzi
Satish Pandey
Tarun Patel
Kevin Piche
Jitendra Prakash
Jason Pye
Hammam Qassim
Nayeli Rodriguez Briones
Allison Sachs
Chung Wai Sandbo Chang
John Schanck
David Schmid
Youn Seok Lee
Ala Shayeghi
Nadine Stritzelberger
Nigar Sultana
Huichen Sun
Ramy Tannous
Theerapat Tansuwannont
Burak Tekcan
Archana Tiwari

Chi Hang (Angus) Kan
Shitikanth Kashyap
Hemant Katiyar
Maria Kieferova
Meenu Kumari
Jason LeGrow
Lin Li
Kai Hong (Nicky) Li
Madelaine Liddy
Piers Lillystone
Guillaume Verdon-Akzam
Sebastian Verschoor
Cameron Vickers
Dhinakaran Vinayagamurthy
Sean Walker
Chunhao Wang
Kyle Willick
Muhammet Yurtalan
Mohd Zeeshan

Master's Students

Shahab Akmal
Matthew Alexander
Thomas Alexander
Julia Amoros (Binefa)
Emma (Annelise) Bergeron
Kristine Boone
Brendan Bramman
Andrew Cameron
Jiahui Chen
Michael Chen
Yutong Dai
Patrick Daley
Simon (Stephanie) Daley
Tina Dekker
Andy (Zhenghao) Ding
Brian Duong
Marcus Edwards
Ryan Ferguson
Ian George
Soumik Ghosh
Adina Goldberg
Lane Gunderman
Melissa Henderson
Nairong Hou
Shih-Chun (Jimmy) Hung
Jaron Huq
Samuel Jaques
Andrew Jena
David Jepson
Andrew Jordan
Connor Kapahi
Jeremy Kelly-Massicotte
Michael (Mike) Kobierski
Michal Kononenko
Nikhil Kotibhaskar
Dariusz Lasecki
Youn Seok Lee
Xudong (Michael) Liu
Guofei (Phillip) Long
Richard Lopp
Pei Jiang Low
Mary Katherine MacPherson
Shayan Majidy
AJ Malcolm
Nicolas Manor
Maria Maristany
Ashutosh Marwah
Morgan Mastrovich
Emma McKay
Denis Melanson
Irene Melgarejo
Kimia Mohammadi
Hamoon Mousavi
Olivier Nahman-Levesque

Maria Papageorgiou
Connor Paul-Paddock
Danny Paulson
Evan Peters
Clifford Plesha
Richard Rademacher
Vinodh Raj Rajagopal Muthu
He (Ricky) Ren
Theodore Rogozinski
Joshua Ruebeck
Romain Ruhlmann
Manas Sajjan
Supratik Sarkar
Nachiket Sherlekar
Jiahao Shi
Yu (Jerry) Shi
Gilbert (Chung-You) Shih
Petar Simidzija
Joshua Skanes-Norman
Sebastian Slaman
Andrew Stasiuk
(Seyed) Sahand Tabatabaei
Erickson Tjoa
Brad van Kasteren
Sam Winnick
Austin Woolverton
Ruoxuan Xu
Bowen Yang
HeeBong Yang
Shazhou (Joey) Zhong

G. Invited Talks and Conference Participation

Faculty Member	Title/Subject	Institution/Conference
Jonathan Baugh	Silicon MOS dots for spin qubits	Technion-Waterloo Joint Symposium, Haifa, Israel, November 2018
	Challenges and opportunities for silicon-based quantum computing	University of Buffalo Physics Seminar, Buffalo, USA, November 2018
	Quantum error correction from fundamentals to practice	Tutorial given at S3S Microelectronics Conference, San Francisco, USA, October 2018
	Challenges and opportunities for spin-based quantum computing in silicon	Department of Materials seminar, Oxford, UK, October 2018
	Challenges and opportunities for spin-based quantum computing in silicon	McMaster University, Engineering Physics seminar, Hamilton, ON, Canada, September 2018
	Network architecture for a topological quantum computer in silicon	Spin Canada Workshop, Calgary, AB, Canada, July 2018
	Quantum transport in nanowires: normal and superconducting regimes	Nanowire Week, Hamilton, ON, contributed, June 2018
	A network architecture for silicon quantum computing	ETCMOS, Whistler, BC, Canada, May 2018
	Challenges in scaling up silicon-based quantum processors	VLSI Test Symposium, San Francisco, USA, April 2018
Kazi Rajibul Islam	Dynamical engineering of spin-spin interaction graphs in a trapped ion quantum simulator	University of Strathclyde Glasgow, UK, November 12, 2018
	Dynamical engineering of spin-spin interaction graphs in a trapped ion quantum simulator	Kavli Institute of Theoretical Physics, UCSB, Santa Barbara, California, USA, August 22, 2018
	Simulating the quantum world with trapped ions	Presidency University, Colloquium Kolkata, India, July 30, 2018
	Simulating programmable frustrated spin systems with a trapped ion quantum simulator	Washington University St Louis Missouri, USA, April 9, 2018
	Quantum simulation with trapped ions	McMaster University, Hamilton, Ontario, Canada
	Many-body states and dynamics workshop	Perimeter Institute and Institute for Quantum Computing, Waterloo, Ontario, Canada
Thomas Jennewein	Fundamental Entanglement Experiments using Quantum Communication Satellites	NASA Workshop on Fundamental Physics, San Diego, USA, April 9. – 11, 2018
	Quantum communication satellites	New Space Technology OECD, Paris, France, April 27, 2018

	Fundamental Quantum Experiments with Quantum Communication Satellites	Quantum Frontiers and Fundamentals 2018 conference supported by Templeton Foundation, Bangalore, India, April 30 –May 4, 2018.
	Quantum Computing for Satellite Communications: a revolution for encrypted communications	UNIDIR 2018 SPACE SECURITY CONFERENCE - SPACE SECURITY: THE NEXT CHAPTER, Geneva, Switzerland, May 7- 8, 2018.
	Gearing up for the Canadian Quantum Communication Satellite Mission	Photonics Society Summer Topical Meeting Series, Hawaii, USA, July 9 – 13, 2018
	Quantum Technology Startups	the Quantum Alberta Workshop, Calgary, Canada, July 18, 2018
	Photonic Quantum Entanglement for Technologies and Applications; Towards the Quantum Internet	The Exner Lectures, Vienna, Austria, October 23, 2018
	Free-space Quantum Key Distribution with trucks, aircraft and satellites	Institute for Quantum Optics and Quantum Information, Vienna, Austria. October 24, 2018
Debbie Leung	A nonlocal game that cannot be played optimally using a finite amount of entanglement	Special Session on Mathematical Perspectives in Quantum Information Theory, Spring Eastern Sectional Meeting, American Mathematical Society, Northeastern University, Boston, USA. April 21–22, 2018.
	Embezzlement-based nonlocal game that cannot be played optimally with finite amount of entanglement	The 15th International Conference on Quantum Physics and Logic (QPL 2018), Dalhousie University, Halifax, Canada. June 3–7, 2018
	Random and pseudo-random unitaries	From Physics to Applications of Quantum Computers, Aspen Center for Physics, Aspen, USA. May 27 – June 17, 2018.
	Embezzlement-based nonlocal game that cannot be played optimally with finite amount of entanglement	Rocky Mountain Summit on Quantum information, JILA, University of Colorado Boulder, Boulder, USA. June 25–29, 2018
	Bell inequality that cannot be maximally violated with finite amount of entanglement	Joint Mathematics Meetings 2019, AMS Special Session on Advances in Quantum Walks, Quantum Simulations, and Related Quantum Theory, Baltimore, USA. January 16–19, 2019
	Making Quantum Information Processing Scalable	2019 AAAS (American Association for the Advancement of Science) Annual Meeting, Symposium “Building Quantum Computers: Why and How”, Washington DC, USA. February 14–17, 2019
Norbert Lütkenhaus	Optical Quantum Communications with Quantitative Advantages	Zeiss International Oberkochen, Germany, April 18, 2018
	Quantum Computing: Security Game Changer	CyCon 2018 Talinn, Estonia, June 1, 2018
	Quantum Communication with Coherent states	CAP Congress Halifax, Nova Scotia, Canada, June 14, 2018
	Quantum Networks	Quantum Internet Workshop Toronto, Ontario, Canada, June 22, 2018

	Crytographic and non-cryptographic network applications and their optical implementation	Quantum Networks - 2018 IEEE Photonics Society Summer Topicals Meeting Series Waikaloa, Hawaii, USA, July 10, 2018
	Optical Quantum Communication Theory - Realizing the Quantum Advantage in QKD and beyond	IQC-China Workshop Waterloo, Ontario, Canada, October 1, 2018
	Quantum Communication with Coherent States of Light	CQuIC Seminar Fall 2018 Albuquerque, New Mexico, USA, December 13, 2018
Adrian Lupascu	Ultrastrong coupling of a single artificial atom to the electromagnetic field	International Workshop for Solid State Quantum Computing Hangzhou, China
	Ultrastrong coupling of a single artificial atom to the electromagnetic field	University of Saarland Saarbruecken, Germany
	Introduction to superconducting qubits	University of Waterloo, Ontario, Canada
Michele Mosca	What Should I Really Do Today About Quantum Computing?	RSA Conference 2018, San Francisco, CA, USA, April 18, 2018
	Computation, Differential Privacy, and Cybersecurity Threats	Orion Think Conference Toronto, ON, Canada, May 2, 2018
	Quantum Update	International Cryptographic Module Conference (ICMC), Canada, May 9, 2018
	Security Session-Disruptive Technologies & Cyberthreat Landscape	Rightscon, Toronto, ON, Canada, May 17, 2018
	Post Quantum Cryptography	MIT online Quantum Computing Practitioner course 2 of 4 that comprises the Applications of Quantum Computing Professional Certificate Program, May 24, 2018
	Workforce Development	Cybersecurity Forum Cambridge, ON, Canada, May 28, 2018
	How do we make the Internet safer without destroying its vitality?	Ditchley Conference, Oxfordshire, UK, June 8, 2018
	Readiness & Impact of Quantum Computing on Cybersecurity & Blockchains	ISACA Toronto Annual Summer Conference 2018 Toronto, ON, Canada, June 24, 2018
	Securing against quantum threats while embracing quantum technology	Webit. Festival Europe 2018 Sofia, Bulgaria, June 27, 2018
	Preparing for the Quantum Era	Crypto2018 Affiliated Event: Quantum-safe Cryptography for Industry, (QsCI) Santa Barbara, CA, USA, August 18, 2018
	Overview of Advances in Quantum Computing and Quantum Cryptography	Quantum-Safe Communications workshop Singapore, July 17, 2018

	The Definitive Need for Crypto-Agility	Information Systems Security Association International (ISSA) Thought Leadership Webinar https://www.issa.org/events/EventDetails.aspx?id=1130964&group=, August 8, 2018
	Prospering in the Quantum Computing Era	iLEAD session at Scotia Bank, Toronto, ON, Canada, September 13, 2018
	Quantum Attacks to Blockchains, Symposium: Can the World Run on Blockchains? The Good, The Bad, and The Ugly	TU Darmstadt Hessen, Germany, September 21, 2018
	Prospering in the quantum computing era	Utimaco Applied Crypto Symposium Silicon Valley San Francisco, CA, USA, November 13, 2018
	The Context of Quantum Security	IDQ 10th Winter School on Quantum Cybersecurity Geneva, Switzerland, January 20, 2019
	Quantum Computing Will Create Jobs but Which Ones?	20th Annual Privacy & Security Conference Victoria, BC, Canada, February 8, 2019
	Commercial QKD & Encryption	OIDA Executive Forum San Francisco, CA, USA, March 4, 2019
	Quantum Computing and Preparing Cyber-Systems for the Post-Quantum Era	RSA Conference San Francisco, CA, USA, March 6, 2019
	"Why Quantum Key Agreement?" as part of the "QKD Hardware Markets"	Inside Quantum Technology, March 20, 2019
Matteo Mariantoni	Two not so Easy Pieces for Superconducting Qubits: Wiring and Coherence	Zhejiang University (Yin's Lab) Hangzhou, China
	Two not so Easy Pieces for Superconducting Qubits: Wiring and Coherence	Zhejiang University (Wang's Lab) Hangzhou, China
	Two not so Easy Pieces for Superconducting Qubits: Wiring and Coherence	Alibaba Inc., DAMO Academy Hangzhou, China
	The Quantum Socket: A Wiring Method for Superconducting Quantum Computing; Materials and Processes for Quantum Computing	American Vacuum Society (AVS) Long Beach, California, USA
	Systems Engineering for Superconducting Quantum Computing	National Institute of Standards and Technology (NIST) Boulder, Colorado, USA
	Systems Engineering for Superconducting Quantum Computing	Peter Grünberg Institute, Jülich, Germany
	Systems Engineering for Superconducting Quantum Computing	Massachusetts Institute of Technology Boston, Massachusetts, USA

	Systems Engineering for Superconducting Quantum Computing	University of Georgia Athens, Georgia, USA
	Systems Engineering for Superconducting Quantum Computing	National Institute of Standards and Technology (NIST)
Guo-Xing Miao	Functionalizing Li ions for data and energy storage	Zhejiang Sci-Tech University Hangzhou China
	Functionalizing Li ions for data and energy storage	Southern University of Science and Technology of China Shenzhen China
	China-IQC conference on quantum Information	Institute for Quantum Computing Waterloo, Ontario, Canada
	Conductance spectroscopy of vertical topological Josephson junction Nb/(Bi0.5Sb0.5)2Te3/ Nb	SPIE-Spintronics XI San Diego, USA
Christopher Wilson	Generation and Distribution of Nonclassical Microwave States	Walter Meisner Institute, Munich, Germany
	Microwave Quantum Radar	Naval Research Lab, Washington, DC, USA
	Nonclassical Light from Superconducting Quantum Circuits	Waveguide QED, Sicily, Italy
	Generation and Distribution of Nonclassical Microwave States	Regensburg University, Regensburg, Germany
	Quantum Innovators Conference	Institute for Quantum Computing, Waterloo, Ontario, Canada
Na Young Kim	Quantum Innovation Laboratory	McGill University, Montreal, Quebec, Canada, April 3, 2018
	Engineered Hopping Integrals of Bloch Exciton-Polaritons	CIFAR, Quebec City, Quebec, Canada, April 6, 2018
	Engineered Hopping Integrals of Bloch Exciton-Polaritons	Hong Kong University of Science and Technology, Hong Kong, China, May 4, 2018
	Solid-state quantum simulator: speculations of biology and medical applications	Hong Kong, China, May 16, 2018
	Exciton-Polariton Quantum Simulators	Imperial College London, United Kingdom, July 18, 2018
	Quantum Innovation Laboratory	Canada-Japan Quantum Computing Conference, July 13, 2018
	Engineered Hopping Integrals of Exciton-Polaritons in Lattices	US-Korea Conference 2018, Queens, NY, USA, August 3, 2018
	The Roles of Academia in Quantum Past, Present, and Future	The AI summit, San Francisco, CA, USA, September 19, 2018
	Quantum Innovation Laboratory	Technion Israel Institute of Technology, Haifa, Israel, November 19, 2018
	Quantum Innovation Laboratory	KAIST, Daejeon, South Korea, December 17, 2018

Kevin Resch	Ultrafast Measurement of Energy-time Entangled States	OSA Application of Lasers for Sensing & Free Space Communication, Orlando, USA (2018)
	Laser and electro-optics	The Optical Society, San Jose, California, USA, May 13, 2018
Christine Muschik	Dissipative quantum error correction and application to quantum sensing with trapped ions	American Physical Society, Boston, Massachusetts, USA, March 4, 2019
	Quantum simulation of problems from high energy physics	Solvay Institutes, Brussels, Belgium, February 18, 2019
	How to simulate high energy physics on a quantum computer	Physics of Quantum Electronics (Winter Colloquium), Salt Lake City, Utah, USA, January 6, 2019
	Quantum simulations of lattice gauge theories	Stony Brook University, Stony Brook, New York, USA, September 10, 2018
	How to simulate models from high energy physics in atomic physics experiments	Max-Planck-Institute, Erlangen, Germany, July 16, 2018
	Quantum simulation of lattice gauge theories	TRIUMF, Vancouver, British Columbia, Canada, June 27, 2018
	How to simulate models from high energy physics in atomic physics experiments	CAP Congress, Halifax, Nova Scotia, Canada, June 11, 2018
	Real-time dynamics of lattice gauge theories with a few-qubit quantum computer	Galileo Galilei Institute for Theoretical Physics, Florence, Italy, June 4, 2018
	Quantum simulations of models from high energy physics	CIFAR, Quebec, Canada, April 2018
	Two-dimensional quantum repeaters	ARL CDQI, Boston, Massachusetts, USA, April 23, 2018
Michal Bajcsy	Photon storage and interactions in cold atomic ensembles inside hollow-core fibers	SPIE Photonics West, San Francisco, California, USA
	Photonic crystals for quantum optics in atomic ensembles (and other assorted efforts)	University of Strathclyde, Glasgow, UK
	Structures for quantum optics with atoms in hollow-core fibres	XLIM, Limoges, France
	Atom-Photon Interactions Chaperoned by Photonic Crystals	Stanford University, Stanford, California, USA
	Quantum Innovators Conference	Institute for Quantum Computing, Waterloo, Ontario, Canada
Vern Paulsen	Free Probability and Applications	Shanks Workshop, Vanderbilt University, Nashville Tennessee, September 2018
	Embedding Problem and Quantum Information Theory	Winter School on Connes, University of Oslo, Oslo, January 2019

Dmitry Pushin	Three Phase-Grating Moire Interferometer	Particle Physics at Neutron Sources, Grenoble, France, May, 2018
	Structured neutron waves from incoherent neutrons	ACNS, College Park, United States, June, 2018
	Structured Waves: From Matter to Light	Applications of Lasers for Sensing and Free Space Communications, Orlando, United States, June, 2018
	The Quantum Neutron	IQC-China, Waterloo, Canada, October, 2018
	Structured neutron waves	SPIE Photonics West OPTO, San Francisco, United States, February, 2019
Crystal Senko	Seminar April 2018	University of Illinois, USA
	Seminar Nov 2018	Perimeter Institute, Waterloo, Ontario, Canada
	Talk IQC-University of Strathclyde Workshop	Institute for Quantum Computing, Waterloo, Ontario, Canada
David Cory	Quantum Information Enabled Neutron Physics	ACNS18, University of Maryland, USA, June 24, 2018
	Overview of Transformative Quantum Technologies	Canadian Graduate Quantum Conference, University of British Columbia, BC, Canada, June 22, 2018
	Quantum Sensing	Future of Mining Workshop, July 11, 2018
	Quantum Opportunities	BMO Investors Group, August 2018
	Impactful, Small Quantum Devices	Quantum Opportunities, October 2018
	Bayes Analysis	CIFAR, Canadian Institute for Advanced Research, October 14, 2018
	Central Spin	CIFAR, Canadian Institute for Advanced Research, October 15, 2018
	Quantum Devices	QuSoft, December 6, 2018
	Innovation Cycle for Quantum Technology	NIST Colloquium, Gaithersburg, MD, USA, December 14, 2018
Adam Wei Tsen	2D Materials for Quantum Devices and Sensing	WBRIN Workshop, Hong Kong, May 16, 2018
	Birth of Van der Waals Spintronics	WIN-CENIDE Workshop, University of Waterloo, Ontario, Canada, June 18, 2018
	Birth of Van der Waals Spintronics	Quantum Alberta Workshop, Calgary, Alberta, Canada, July 18, 2018
	New Phase Transitions in Atomically Thin Quantum Materials	Department of Physics Condensed Matter Seminar, University of Minnesota, USA, October 31, 2018
	New Phase Transitions in Atomically Thin Quantum Materials	Department of Physics Colloquium, University of Ottawa, Ontario, Canada, December 6, 2018

H. Seminars and Colloquia

Colloquia

Quantum weak coin flipping	Jeremie Roland
Quantum steampunk: Quantum information meets thermodynamics	Nicole Yunger Halpern
Custom low-dimensional material systems explored at the atomic scale	Adina Luican-Mayer
Ultrasound and Cooperative Light-Matter coupling	Junichiro Kono
Battling in the realm of a topological superconductor candidate: Sr_2RuO_4	Wen Huang
Heat bath algorithmic cooling with thermal operations	Alvaro Alhambra
The European Spallation Source: The Next-Generation Neutron	Ken Andersen
Quantum Algorithms for Classical Probability Distributions	Alexander Belovs
Quadratic speedup in finding a marked vertex via quantum walk	Stacey Jeffery
Quantum Algorithms for Composed Functions with Shared Inputs	Justin Thaler
Quantum proof systems for iterated exponential time and beyond	Henry Yuen
Trapped Ion Experiments at Sandia National Laboratories	Susan Clark
New forms of matter with ultracold atoms: synthetic magnetic fields and super solidity	Wolfgang Ketterle
Asymptotic performance of port-based teleportation	Felix Leditzky
Probing many-body interactions using entangled photons: theory and thoughts for experiments	Eric Bittner
The Polynomial Method Strikes Back: Tight Quantum Query Bounds via Dual Polynomials	Robin Kothari
Spatial noise filtering through error correction for quantum sensing	David Layden
Excitations in Topological Superfluid ^3He	Yoonseok Lee
Quantum Annealing with Non-stoquastic Hamiltonians	Layla Hormozi
Spatial Isolation implies unconditional zero knowledge, even with entanglement	Nick Spooner
Quantum metrology gets real	Konrad Banaszek

Seminars

Mess Suppression and Emergent Symmetries of Strong interactions	Martin Savage
Real algebra, random walks, and information theory	Tobias Fritz
How to learn a Quantum state	John Wright
Gap-independent cooling and hybrid quantum-classical annealing (HQCA)	Peter Schumacher
Operating noisy quantum computers	Joel Wallman
Quantum coherence manipulation with finite resources	Kun Fang
Quantum assisted magnetic resonance across length scales	Ashok Ajoy
Ultracold Molecules: From Quantum Chemistry to Quantum computing	Alan Jamison

Exploring Synthetic Quantum Matter in Superconducting Circuits	Alex Ruichao Ma
A microwave optomechanical circuit with parametric mechanical driving	Shun Yanai
Quantized States, Berry Phases, and Quantum-Hall Wedding-Cake structures in Graphene	Sayeh Rajabi
Quantum Dots	Fereshte Gharhari Kermani
Microwave quantum devices based on Josephson photonics	Max Hofheinz
Alkaline-Earth atoms in Optical Tweezers	Alexandre Cooper-Roy
The potential applications of quantum computation in exploration geophysics	Shahpoor Moradi
Limitations on the use of Heisenberg picture	James Franson
Quantum Chebyshev's inequality and applications	Frederic Magniez
Quantum Range finding	Stefan Frick
Quantum-assisted quantum compiling (arXiv:1807:00800)	Sumeet Khatri
Quantum advantage in Learning Parity with Noise	Daniel Kyungdeok Park
From estimation of quantum probabilities to simulation of quantum circuits	Hakop Pashayan
Using macroscopic quantum systems as detectors	Swati Singh
Dynamical control of superconductors and ultracold atoms	Ludwig Mathey
Modeling Interactions between Hydrophobic Nanosheets and Lipid Membranes	Jun Fan
Proposal for Quantum Simulation via All Optically Generated Tensor Network states	Ish Dhand
RF Phase-Shifting System Based on YBCO Superconducting Thin Films	Eldad Holdengreber
Dynamics of quantum coherence in non-equilibrium many-body	Salil Bedkihal
Quantum Simulation of Mesoscopic Fermi Systems	Philipp Preiss
Dissipative stabilization and manipulation of Schrodinger cat states for quantum error correction	Alexander Grimm
Exotic hadrons from lattice QCD	Randy Lewis
Scaling up superconducting quantum computers	David P. Pappas
Maximal Coherence and the Resource Theory of Purity	Dagmar Bruss
Asymptotic limits in quantum frequency estimation	Jan Haase
Mind the gap: Cheeger inequalities and adiabatic algorithms	Michael Jarret
Cryogenic Dissipation in Nanoscale Optomechanical Cavities	Bradley Hauer
"Free-space" Chiral Quantum Optics and a "Few-Atom" Quantum Antenna	Peter Zoller
Space-time density matrix for continuous variables	Tian Zhang
A quantum information perspective on spectroscopy	Raul Garcia-Patron
Past quantum state for continuous variable systems	Jinglei Zhang
Quantum nondemolition measurement of mechanical motion quanta	Luca Dellantonio
A Connection between gentle measurement of quantum states and differential privacy	Scott Aaronson
Nonlocal games with synchronous correlations	Brad Lackey
Selection of unitary operations in quantum secret sharing protocols without entanglement	Juan Xu

I. Scientific Visitors

Visitor Affiliation	Country
Tsinghua University	China
University of Innsbruck	Austria
University of Chicago	USA
The College of William and Mary	USA
University of Illinois	USA
University of Alberta	Canada
University of Florida	USA
Massachusetts Institute of Technology	USA
Perimeter Institute	Canada
Microsoft Research	USA
University of Houston	USA
The University of British Columbia	Canada
University of Science and Technology of China	China
University of Colorado, Boulder	USA
National Institute of Technology, Rourkela	India
University of Virginia	USA
The Institute of Photonic Sciences	Spain
Indian Institute of Technology (IIT)	India
Indian Institute of Technology Bombay	India
Universität Ulm	Germany
University of Southern California	USA
Delft University of Technology	Netherlands
University of Chile	Chile
University of Duesseldorf	Germany
Yeshiva University	USA
National Autonomous University of Mexico	Mexico
Yale University	USA
National Institute of Standards and Technology	USA
York University	Canada
The University of Technology	Australia
Tsinghua University	China
Queen's University	UK
Birla Institute of Technology and Science	India

Visitor Affiliation	Country
Universitat Stuttgart	Germany
Fudan University	China
Bellevue College, Washington	USA
University College Dublin	Ireland
Heidelberg University	USA
University of Technology, Sydney	Australia
NIC/DESY Zeuthen, Germany	Germany
Brandon University	Canada
Federal University of ABC	Brazil
Hong Kong University of Science and Technology	Hong Kong
University of Warsaw	Poland
Institut für Quanteninformation RWTH Aachen	Germany
Peking University	China
University of Maryland	USA
Birla Institute of Technology and Science	India
Stanford University	USA
State University of New York at Buffalo	USA
Tsinghua University	China
Technion – Israel Institute of Technology	Israel
Massachusetts Institute of Technology	USA
Tsinghua University	China
University of Electronic Science and Technology of China	China
Tsinghua University	China
Massachusetts Institute of Technology	USA
Raytheon-BBN Technologies	Canada
Raytheon-BBN Technologies	Canada
University of Strathclyde	UK
University of Copenhagen	Denmark
Aarhus University	Denmark
Fudan University	China
Fudan University	China
University of Southern California	USA
Macquarie University	Australia
University of Bristol	UK
QuIC - Université libre de Bruxelles	Belgium
Nanjing University of Aeronautics and Astronautics	China
Montana State University	USA
National University of Ireland	Ireland
IQC Board Member	Canada

Visitor Affiliation	Country
IQC Board Member	Canada
Lakehead University	Canada
University of Oxford	UK
Massachusetts Institute of Technology	USA
University of Exeter, UK	UK
Centre for Theoretical Studies, Indian Institute of Technology	India
Nanjing University	China
Ariel University	Israel
Anyon Systems	Canada
University of Sydney	Australia
Institute for Quantum Optics and Quantum Information	Austria
Institute for Quantum Science and Engineering	USA
University of Ulm	Germany
IBM TJ Watson Research Center	USA
Korea research institute of standard and science	South Korea
University of Maryland	USA
NIC/DESY Zeuthen	Germany
University College London	UK
Sandia National Laboratories	USA
Raman Research Institute	India
Jiaotong University	China
University of Electronic Science and Technology of China	China
University of Toronto	Canada
City University of Hong Kong	Hong Kong
Institut Laue-Langevin	France
Beijing Normal University	China
Chinese Academy of Science	China
University of Hamburg	Germany
University of Delaware	USA
The University of Sydney	Australia
University of Manitoba	Canada
Korea Advanced Institute of Science and Technology	South Korea
Georgetown University	USA
Kyoto University	Japan
Louisiana State University	USA
Fudan University	China
Fudan University	China
QuSoft, Research Centre for Quantum Software	Netherlands
University of Notre Dame	USA

Visitor Affiliation	Country
University of British Columbia	Canada
University of Bristol	UK
University of Latvia	Latvia
NIC/DESY Zeuthen	Germany
Tsinghua University	China
Université Paris Diderot	France
University of Science and Technology of China	China
University of Toronto	Canada
Lorraine Research Laboratory in Computer Science	France
Neutron Instruments Division, European Spallation	Sweden
Defence Research and Development Canada	Canada
The University of British Columbia	Canada
University of Maryland	USA
Turgut Özal University	Turkey
University of Chicago	USA
University of Calgary	Canada
Charles University	Czech Republic
Perimeter Institute	Canada
California Institute of Technology	USA
University of Sherbrooke	Canada
National Institute of Standards and Technology	USA
Delft University of Technology	Netherlands
Queen's University	Canada
McMaster University	Canada
McMaster University	Canada
Princeton University	USA
Shenzhen Peng Cheng Laboratory	China
Massachusetts Institute of Technology	USA
University of California	USA
Temple University	USA
Imperial College London	UK
Princeton University	USA
Technion – Israel Institute of Technology	Israel
Universität des Saarlandes	Germany
Amherst College	USA
University of Cambridge	UK
University De Sao Paulo	Brazil
The University of California	USA
Rice University	USA

Visitor Affiliation	Country
Massachusetts Institute of Technology	USA
Mississippi State University	USA
University of California	USA
Michigan State University	USA
Perimeter Institute	Canada

J. Tours – Industry, Government and Academic

Company/Organization	# Visitors
Academic	
University of Adelaide: President and Pro-Vice Chancellor	2
Advancement Event	5
Queen's University	20
University of Guelph QI Undergraduates	7
Perimeter Scholar's International Students	15
Prospective Graduate Students	7
Security Proofs in QKD workshop delegates	26
Government	
NRC	1
Global Senior Trade Commissioners from Global Affairs Canada	21
Invest Canada	2
Canadian Ambassador to China	3
US NRL	5
Industry	
Ontario Procurement Management Association	31
Alibaba	15
Bohr Technologies	3
1Qubit	2
Ocado	1
Rank Group	1
X (formerly known as Google X)	3
CSS Security (visitors of Isara)	4
Verdexus; Nova LVX; Switzerland; Lyceum Capital, UK	3
Comcast and SSIMWAVE	5
North (formerly Thalmic Labs)	4
Maria Gotsch (Partnership for New York City)	1
QVI	3
TCI Network Global Conference, Emerging Tech Cluster Immersion Experience (Communitech)	25
DRIVE Conference	35
Private individuals	12
IQC-China Quantum Technologies Conference delegates	60
Harnessing Quantum Technologies Open House visitors	120

K. Earned Media

The full list of earned media is available upon request.

L. Governance

Below is a biography for individuals currently servicing on IQC's Executive Committee, Board of Directors and Scientific Advisory Committee.

Executive Committee

Kevin Resch, Interim Executive Director

Kevin Resch received a BSc (Hon.) degree in Chemical Physics from Queen's University, Kingston, Canada, in 1997. He received MSc and PhD degrees in Physics from the University of Toronto, Canada, in 1998 and 2002 respectively. His Masters and Doctoral theses were based on experimental quantum optics and completed under the supervision of Aephraim Steinberg. Subsequently, Kevin held a Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship with Anton Zeilinger's group at the University of Vienna, Austria and a Research Fellow position with Andrew White's Quantum Technology Laboratory at the University of Queensland, Brisbane, Australia. He joined the University of Waterloo's Department of Physics and the Institute for Quantum Computing (IQC) in 2006.

Charmaine Dean, Vice President, Research and International, University of Waterloo

Charmaine Dean is Vice-President, Research and International, and Professor in the Department of Statistics and Actuarial Science at the University of Waterloo. Her research interest lies in the development of methodology for disease mapping, longitudinal studies, the design of clinical trials, and spatio-temporal analyses. Much of this work has been motivated by direct applications to important practical problems in biostatistics and ecology. Her current main research applications are in survival after coronary artery bypass surgery, mapping disease and mortality rates, forest ecology, fire management, smoke exposure estimation from satellite imagery, and modeling of temporary and intermittent stream flow for flood analysis and predictions.

Bob Lemieux, Dean of Science, University of Waterloo

Dr. Bob Lemieux joined Waterloo as the Dean of Science starting July 1, 2015. Previous to his appointment here, he was a professor in the Department of Chemistry and served as Associate Dean (Research) in the Faculty of Arts and Science at Queen's University. Bob Lemieux came with proven experience as an administrator, researcher, mentor and teacher. His passion for teamwork and collaboration has helped him create a culture of synergistic partnerships across academic units and faculties. Lemieux has been a faculty member of Department of Chemistry at Queen's University since 1992. His multi-disciplinary research into designing advanced liquid crystal materials found in high-performance microdisplays has earned him several international recognitions, including the 2012 Samsung Mid-Career Award and the Ontario Premier's Research Excellence Award. He is co-investigator on a CREATE grant. Lemieux received the Chemistry departmental teaching award twice as well as the W.J. Barnes Teaching Excellence Award from the Queen's Arts and Science Undergraduate Society. Lemieux was Head of the

Chemistry Department for five years and Associate Dean (Research) in the Faculty of Arts and Science at Queen's University, and has also been involved in the recruitment of a Canada Excellence Research Chair.

Pearl Sullivan, Dean, Faculty of Engineering, University of Waterloo

Pearl Sullivan received her BEng with distinction (1985) and MASc (1986) degrees from the Technical University of Nova Scotia in metallurgical engineering. In 1990, she earned a PhD from the University of British Columbia in materials engineering, specializing in the failure of 131 carbon-fibre reinforced composite materials. Dr. Sullivan started her academic career at Nanyang Technological University, Singapore, in 1991 before returning to Canada in 1994 to join the Department of Mechanical Engineering at the University of New Brunswick. She was twice honoured with the UNB Faculty Merit Award for Excellence.

In 2004, Dr. Sullivan became a faculty member of the University of Waterloo's Department of Mechanical and Mechatronics Engineering and served as its Department Chair from 2006 to 2011. She was recognized with the university's Outstanding Performance Award in 2009. A strong believer in interdisciplinary research, she was the founding Director of the collaborative graduate program in Nanotechnology within the university's Faculties of Engineering and Science. Dr. Sullivan began her term as Dean of Engineering in July 2012.

Stephen Watt, Dean, Faculty of Mathematics, University of Waterloo

Stephen M. Watt is Dean of the Faculty of Mathematics and Professor in the David R. Cheriton School of Computer Science at the University of Waterloo. He previously held the title of Distinguished University Professor at Western University where he served for periods as Chair of the Department of Computer Science and Director of the Ontario Research Centre for Computer Algebra. Prior to this, he held positions at the IBM T.J. Watson Research Center in Yorktown Heights (USA) and INRIA and the University of Nice (France). Professor Watt's areas of research include algorithms and systems for computer algebra, programming languages and compilers, mathematical handwriting recognition and document analysis. He was one of the original authors of the Maple and Axiom computer algebra systems, principal architect of the Aldor programming language and its compiler at IBM Research, and is co-author of the MathML and InkML W3C standards. Watt was a co-founder of Maplesoft in 1988 and served on its board of directors from 1998 to 2009. He served on the board of directors of the Descartes Systems Group from 2001 to 2015, including two periods as Board Chair. He presently serves on the boards of Waste Diversion Ontario, which oversees the management of all Ontario's recycling programs, and of the McMichael Canadian Art Foundation. Professor Watt is the recipient of numerous distinctions, including Doctor Honoris Causa from the University of the West (Romania), the J.W. Graham Medal in Computing and Innovation (Waterloo) and the Outstanding Innovation Award (IBM).

Board of Directors

Mike Lazaridis (Board Chair) Co-founder and Managing Partner, Quantum Valley Investments

Mike Lazaridis the founder of telecommunications company Blackberry (formerly Research In Motion). He served as Vice Chair of the company's Board, and Chair of the Board's new Innovation Committee. IQC was launched in 2002 thanks to the vision and incredible philanthropy of Lazaridis, who has given more than $105 million to the institute since inception. He is also the founder of Waterloo's Perimeter Institute for Theoretical Physics.

Tom Brzustowski, RBC Professor, Telfer School of Management, University of Ottawa

Tom Brzustowski graduated with a B.A.Sc. in Engineering Physics from the University of Toronto in 1958, and a PhD in Aeronautical Engineering from Princeton in 1963. He was a professor in the Department of Mechanical Engineering at the University of Waterloo from 1962 to 1987. He served as Chair of Mechanical Engineering from 1967 to 1970 and as Vice President, Academic of the university from 1975 to 1987. He served as deputy minister in the Government of Ontario from 1987 to 1995. He was appointed President of NSERC in October 1995, and reappointed in 2000. He is an Officer of the Order of Canada and a fellow of the Canadian Academy of Engineering and of the Royal Society of Canada.

Charmaine Dean, Vice President, Research and International, University of Waterloo

Complete biography listed under Executive Committee.

Robert Dunlop, Retired, Industry Canada

Robert recently retired from Industry Canada where he was the assistant deputy minister responsible for science and innovation. He held this position between 2009 and 2014, and before that he served at the assistant deputy minister level at Finance Canada where he co-managed the Economic Development and Corporate Finance Branch. Over his career he had responsibilities in a number of areas including program management, policy development and supporting ministers. Robert is a native Montrealer where he studied economics and finance at McGill University. He now lives in Toronto.

Cosimo Fiorenza, VP and General Counsel, Quantum Valley Investments

Cosimo Fiorenza, Vice-Chair, has played a major role in the development of the Quantum Valley in Waterloo Region. He is a founding member of the Perimeter Institute Board of Directors. In addition to his role as Vice-Chair of the Board, Mr. Fiorenza is a member of both the Finance Committee and the Investment Committee, and previously served as Co-Chair of the Perimeter Institute Leadership Council. He is also the Chair of the Board of Directors of Friends of Perimeter Institute and a member of the Board of Directors of AIMS-NEI Canada, one of Perimeter¹s global outreach partners.

Mr. Fiorenza is the Vice-President and General Counsel of Quantum Valley Investments, where he has helped to establish numerous quantum technology start-up companies. He serves as a director and officer of several of these start-up companies, actively supporting them in a broad

spectrum of matters including recruitment, financial matters, intellectual property, fundraising, and government relations.

Mr. Fiorenza also helped to establish the Institute for Quantum Computing at the University of Waterloo and remains an active member of the IQC Board of Directors and Finance Committee. In 2016, he helped establish Quantum Valley Ideas Lab, a charitable organization focused on applied quantum research and specifically the development of new quantum technologies that will be the basis for new products and new businesses in Canada. Mr. Fiorenza serves as Vice-Chair of Ideas Lab and is also a member of its Finance Committee and Investment Committee. Previously, he spent approximately 20 years with major Toronto law firms, advising some of Canada¹s leading corporations and entrepreneurs on income tax and commercial matters, with a focus on technology and international structure. Mr. Fiorenza holds a degree in business administration from Lakehead University and a law degree from the University of Ottawa. He was called to the Bar in Ontario in 1991.

Mark Pecen, CEO, Approach Infinity Inc.

Mark Pecen serves as CEO of Approach Infinity, Inc., providing advisory services to firms requiring technology due diligence and management consulting in the areas of wireless communication and emerging technologies, rapidly growing technology companies and their venture capital funding partners. The firm comprises a network of senior executives and experts in the management of technology, innovation, research and development, marketing, sales, global standards, patents, technology entrepreneurship, and individuals with specific technical disciplines such as information theory, radio frequency systems, wireless system protocols, cryptography and others. Pecen retired as Sr. Vice President, Research and Advanced Technology and technology advisor to the CEO of BlackBerry, maker of wireless smart phones. He was responsible for the creation and management of BlackBerry's Advanced Technology Research Centre and a significant portion of BlackBerry's wireless patent portfolio. A past Distinguished Innovator and member of the Science Advisory Board at Motorola, Pecen also managed consultation work for clients in North America and Europe.

David Fransen, Former Consul General Canadian Consulate in Los Angeles

David Fransen worked from 1985 to 1988 at the Privy Council Office, where he provided policy advice related to such developments as the Green Plan in 1990, the drafting of the Canadian Environmental Assessment Act and the Canadian Environmental Protection Act, and the creation of the Canadian Environmental Assessment Agency. He then became Director of Economic Framework Policies in the Strategic Policy Branch of Industry Canada. In 1999, David became the Director General of the Centre for Healthy Human Development at Health Canada. He became Assistant Deputy Minister of the Industry Sector in 2003, where he was primarily responsible for providing policy advice and delivering programs related to some of Canada's key economic sectors. He became executive director of the Institute for Quantum Computing in 2006. He was most recently the Consul General, Canadian Consulate General in Los Angeles.

Wayne Kozun, Former Senior Vice-President, Public Equities, Ontario Teachers' Pension Plan Board

Wayne Kozun was responsible for Ontario Teachers' Public Equities portfolio. Public Equities incorporates internally managed portfolios, the Relationship Investing team and external managers used primarily to broaden geographic scope. In support of these activities, Public Equities monitors the corporate governance practices of the companies in which Ontario Teachers' invests. Wayne joined Ontario Teachers' in 1995 and has held various positions including most recently Senior Vice-President, Fixed Income & Alternative Investments. Wayne serves on the boards of the Canadian Coalition for Good Governance, the Pacific Pension & Investment Institute and Camelot UK Lotteries Ltd. He holds a BESc from Western University, and MBA from the Ivey Business School, is a CFA charterholder, and is a graduate of the Institute of Corporate Directors.

Scientific Advisory Committee

Prof. Chris Monroe, University of Maryland (Chair)

Christopher Monroe is an experimental atomic, molecular and optical physicist. Monroe obtained his PhD at the University of Colorado in 1992. From 1992-2000, Monroe was a postdoc and staff physicist in the Ion Storage Group of David Wineland at the National Institute of Standards and Technology in Boulder, CO. In 2000, Monroe moved to the University of Michigan, where he introduced the use of single photons to couple quantum information between atomic ions. In 2006, he became Director of the FOCUS Center at the University of Michigan. In 2007, Monroe became the Bice Sechi-Zorn Professor of Physics at the University of Maryland and a Fellow of the new Joint Quantum Institute betweeryland and NIST. In 2007-2008, Monroe's group succeeded in producing quantum entanglement between two widely separated atoms and teleported quantum information between atoms separated by a large distance.

Prof. Harry Buhrman, Centrum voor Wiskunde en Informatica (CWI)

Harry Buhrman is head of the research group 'Algorithms and Complexity' at the Centrum Wiskunde & Informatica, which he joined in 1994. Since 2000 he also has a joint appointment as full professor of computer science at the University of Amsterdam. Buhrman's research focuses on quantum computing, algorithms, complexity theory, and computational biology. One of the highlights in the work of Buhrman is the article co-authored with Richard Cleve (University of Waterloo, Canada) 'Quantum Entanglement and Communication Complexity'. They demonstrated that with quantum entanglement certain communication tasks can be solved more efficiently. He also co-developed a general method to establish the limitations of quantum computers. He has written more than 100 scientific publications.

Prof. Anthony Leggett, University of Illinois at Urbana-Champaign

Anthony J. Leggett, the John D. and Catherine T. MacArthur Professor and Center for

Advanced Study Professor of Physics, has been a faculty member at Illinois since 1983. He was a co-winner of the 2003 Nobel Prize in Physics for pioneering work on superfluidity. He is a member of the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences, the Russian Academy of Sciences (foreign member), and is a Fellow of the Royal Society (U.K.), the American Physical Society, and the American Institute of Physics. He is an Honorary Fellow of the Institute of Physics (U.K.).
He was knighted (KBE) by Queen Elizabeth II in 2004 "for services to physics." He is also a Mike and Ophelia Lazaridis Distinguished Research Chair.

Umesh Vazirani, University of California

Umesh Vazirani is a professor in the Computer Science Division of the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. Professor Vazirani is a Director of the Berkeley Quantum Information and Computation Center (BQIC). He received an NSF Presidential Young Investigator Award in 1987 and the Friedman Mathematics Prize in 1985. Professor Vazirani wrote the book, “An Introduction to Computational Learning Theory" with Michael Kearns and currently is at the forefront of research in the area of quantum computing.

Prof. Anton Zeilinger, University of Vienna

Anton Zeilinger is a professor of physics at the University of Vienna (previously Innsbruck). Professor Zeilinger is known for multiple experiments in the realm of quantum interferometry and the demonstration of quantum teleportation. His work influenced the experimental progress in a new sub-field of physics, quantum information theory. He has contributed to theoretical physics and the foundations of quantum mechanics — he has showed an amplification of the Einstein-Podolsky-Rosen paradox, where one considers three, instead of just two, entangled particles.

Prof. Wojciech Zurek, Los Alamos National Laboratory

Wojciech Hubert Zurek is a Laboratory Fellow at Los Alamos National Laboratory (LANL). He is a leading authority on a number of physics topics, including quantum theory, and particularly, decoherence. His work also has great potential benefit to the emerging field of quantum computing. He was educated in Krakow, Poland (M.Sc. 1974) and Austin, Texas (PhD 1979). He spent two years at Caltech as a Tolman Fellow, and began his appointment at LANL as a J. Oppenheimer Fellow. He was the leader of the Theoretical Astrophysics Group at LANL from 1991 until he was made a Laboratory Fellow in the Theory Division in 1996. Zurek is currently a foreign associate of the Cosmology Program of the Canadian Institute for Advanced Research.

M. Administrative Staff

IQC Administrative Staff as of March 31, 2019:

Taso Alkiviades
Jeannie Bairos
Emma Bartlett
Erica Boland
Maren Butcher
Sara Clark
Matt Coper
Hillary Dawkins
Monica Day
Emma DeSousa
Christine Dietrich
Greg Digulla
Melissa Donnelly
John Donohue
Lino Eugene
Kathryn Fedy
Guanru Feng
Tracey Forrest
Matt Fries
Yufei Ge
Sandra Gibson
Brian Goddard
Stefan Heinemann
Brendon Higgins
Shoshannah Holdom
Greg Holloway
Taminiau Ivar
Sofija Jelacic
Lana Kovacevic
Kim Kuntz
Jisu Kwon
Deler Langenber
Chin Lee
Vito Logiudice
Rachel Marriott
Kaitlyn McDonell
Brian Moffat
Mai-Britt Mogensen
Brian Neill
Nathan Nelson-Fitzpatrick
Adele Newton
Angela Olano
Mary Lyn Payerl
Michele Roche
Alex Rollinson
Roberto Romero
Rodello Salandanan
Matt Schumacher
Matt Scott
Peter Sprenger
Siobhan Stables
Harmeny Storer

Dylan Totzke

Carly Turnbull

Andrew Turski

Tarralee Weber

Steve Weiss

Adam Winick

N. Financial Information – Auditor's Report

Please see accompanying *IQC F19 ISED Auditors' Report*.