



Annual Report **April 1, 2021 – March 31, 2022**

**For submission to the Ministry of Innovation, Science and
Economic Development
July 31, 2022**





FROM THE EXECUTIVE DIRECTOR

Fiscal 2021-2022 was a year of renewal at the Institute for Quantum Computing (IQC). New executive and managerial leadership, a new corporate structure and a new Executive committee are in place for IQC's 20th anniversary, and we are looking forward to building on the successes we have created over the last 20 years.

Thanks to the continued commitment and support of the Federal Government, IQC and Canada stand among the top quantum centres worldwide. Over the past year, we have contributed to global quantum knowledge with 172 published papers, 130 presentations and 175 ongoing, international collaborations. Our graduate program attracted 208 students from across the globe and we launched our new course-based master's program, tailored to producing the kinds of highly qualified professionals the emerging quantum industry needs for continued growth.

The academic successes of IQC combined with the entrepreneurial spirit at the University of Waterloo has created an environment, the Quantum Valley, where growth is occurring at each of our three locations (the Mike and Ophelia Lazaridis Quantum-Nano Centre, and the two Research Advancement Centre buildings). In addition to supporting the laboratory requirements of our faculty, IQC also supports the Quantum-Nano Fabrication and Characterization Facility which directly support the needs of academic groups across the country and makes available advanced manufacturing techniques that keep newly founded industries in Canada.

A full 40% of IQC faculty are now involved with start-ups at the executive level, spinning off businesses that will improve the resolution of MRIs, create more advanced metrology tools, and secure communications for the post-quantum era that is emerging. In May 2021, one of these start-ups was acquired by a large multi-national corporation but continues to operate in the Waterloo Region due to the collective knowledge and technical expertise that exist in the area. The future looks bright as we discover and commercialize powerful new technologies. We look forward to these technologies playing a transformational role in the future of Canada and the lives of Canadians.

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

Sincerely,



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



Table of Contents

EXECUTIVE SUMMARY	3
INSTITUTE FOR QUANTUM COMPUTING	4
FUNDING OBJECTIVES	5
Objective A.....	6
Objective B.....	40
Objective C.....	52
Objective D.....	58
Objective E.....	67
APPENDICES	70
A. Risk Assessment & Mitigation.....	70
B. Publications.....	72
C. Faculty Members, Research Assistant Professors & Research Associates.....	79
D. Collaborations – April 1, 2021 – March 31, 2022	81
E. Postdoctoral Fellows.....	86
F. Graduate Students	87
G. Invited Talks & Conference Participation	90
H. Scientific Visitors & Tours	96



EXECUTIVE SUMMARY

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

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

Highlights from the 2021-2022 year, include:

- Attracted over \$29,700,000+ in funding
- Recruited 1 new faculty member and 10 research associates
- Welcomed 12 new postdoctoral fellows
- Published 172 papers in peer-reviewed journals
- Reached almost 75,000 cumulative citations
- Delivered presentations to 130 academic peer groups across Canada and the globe with more than 175 ongoing collaborations
- Attracted 510+ applications from across Canada and the world to graduate programs, resulting in a 5% increase in students identifying as female
- Over 550 awards received by IQC graduate students
- Hosted two workshops, 39 seminars, 3 colloquia, and sponsored 8 external scientific programs
- The IQC YouTube channel garnered over 199,000 views and over 21,500 hours of watch time
- Launched a new course-based master's program, tailored to developing industry professionals, with the first graduates expected in August 2022

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



INSTITUTE FOR QUANTUM COMPUTING

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

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

None of this would be possible without the visionary leadership and investments of Mike and Ophelia Lazaridis, the Government of Canada, the Government of Ontario and the University of Waterloo. This strategic private-public partnership has accelerated the advancement of quantum information research and discovery not only in Canada, but around the globe.

Vision & Mission

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

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

Strategic Objectives

IQC is guided by strategic objectives developed in partnership with the Government of Canada in 2008:

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

FUNDING OBJECTIVES

2019-2022

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

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

The activities planned and undertaken by IQC with the support of the Government of Canada over the past 3 years has positioned Canada to take full advantage of socioeconomic benefits of quantum research and technology. What follows is progress achieved in the 2021-2022 year.

Objective A

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

Expected Result: Increase knowledge in quantum information and technology.

Planned Activities:

- Leveraging talent from across three University of Waterloo faculties — Engineering, Mathematics and Science — researchers will continue IQC’s collaborative and interdisciplinary research agenda in quantum computation, quantum communication, quantum sensors and quantum materials
- Publishing research results in globally recognized journals
- Recruiting new faculty members, research assistant professors and research associates
- Continuing to outfit labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre as new IQC members are recruited
- Continuing to outfit and maintain the Quantum Nano Fabrication and Characterization Facility to enable fabrication of quantum-enabled technologies
- Updating and maintaining laboratory space in the Research Advancement Centre (RAC) buildings
- Continuing effective and relevant relationships with current research partners
- Seeking out new partnerships that will advance IQC’s mission and strategic objectives



Research Publications & Citations

In 2021-2022, IQC researchers collectively published 172 papers in peer-reviewed journals bringing the cumulative number of publications to 2603¹ since 2002. Several papers appear in prominent scientific publications including Science, the Nature family, the Journal of Mathematical Physics and Physical Review Letters. Below is a summary of articles published in prominent journals since 2015. A full list of all papers published this year can be found in Appendix B beginning on page 72.

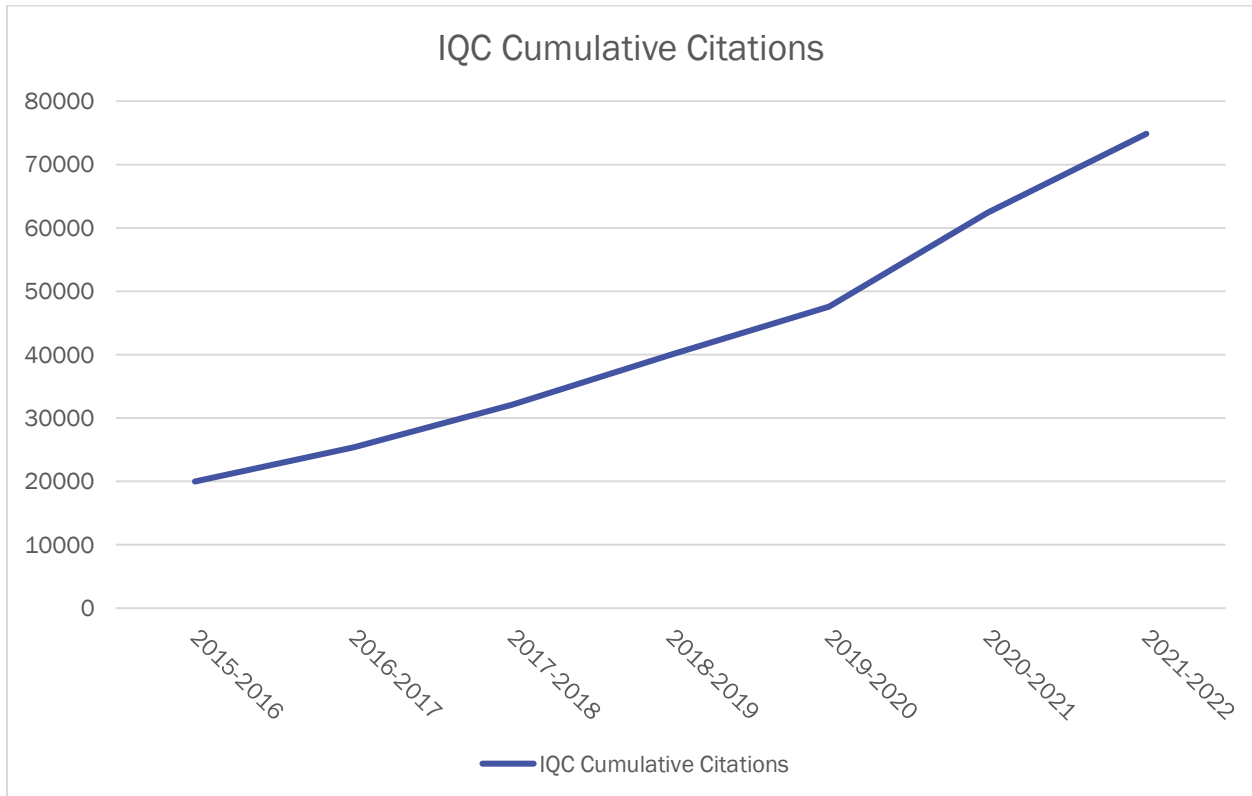
Prominent Publications	15-16	16-17	17-18	18-19	19-20	20-21	21-22
Family of Nature Journals	7	9	9	4	9	12	11
Physical Review Letters	17	11	6	8	15	8	10
Science				1			2
Journal of Mathematical Physics	7	3	4	5	1	3	1
FOCSs	2	1			9	1	0
STOC	1	2	1	1	1	3	0
QIP	5	5	10	11	11	5	7

Further analysis reveals that 69% of IQC papers (from 2016 through to the present) have been published with international collaborators from leading universities and institutes including Massachusetts Institute of Technology (MIT), University of Maryland, Delft University of Technology, Tsinghua University, Université de Sherbrooke, University of British Columbia and University of Toronto.

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



Citations are also an important indicator of the influence of published research. As of March 31, 2022, the number of cumulative citations from IQC's published papers reached 74,855. The growth chart below highlights the large increases in IQC citations given the moderate faculty growth, highlighting the significant impact of IQC researchers on global quantum research.



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

Research Highlights

The following stories represent a sample of the research published at IQC over the past year. These stories serve to highlight the breadth and depth of the research produced at the Institute.

REDUCING THE INFINITE FOR QUANTUM COMMUNICATION

Published in PRX Quantum on May 24, 2021

<https://journals.aps.org/prxquantum/pdf/10.1103/PRXQuantum.2.020325>

IQC researchers have developed a method to simplify the analysis of quantum communication protocols compatible with existing telecommunications infrastructure.

One of the exciting technologies enabled by quantum mechanics is quantum key distribution (QKD), which allows two parties to establish a shared, secret key protected by the laws of nature. The two parties can detect if an eavesdropper attempts to interfere

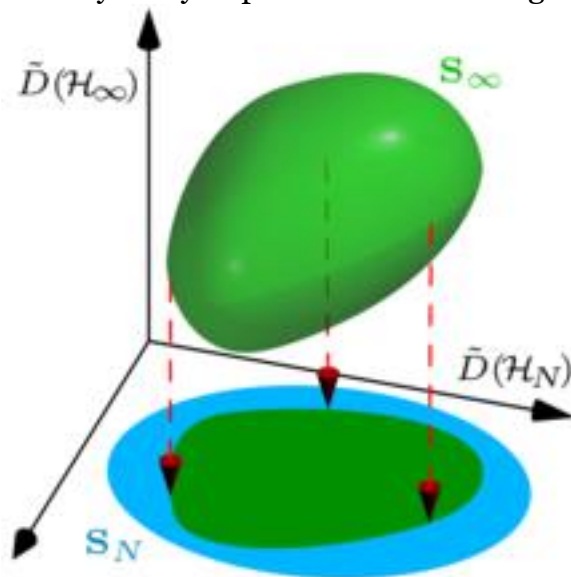
with their communication, which is not possible using classical systems. If significant eavesdropping activity is detected, the parties can simply abandon the protocol and try again.

“The exciting thing about quantum key distribution is that it is already being implemented experimentally,” said Twesh Upadhyaya, a master’s student at IQC and the Department of Physics and Astronomy, and lead author on the paper. “With the right protocols, QKD can even be implemented on a large scale using existing telecommunications infrastructure.”


The problem? These protocols are much more challenging to analyze.

Information is encoded into pulses of laser light sent from Alice to Bob. After an eavesdropper, Eve, interacts with the pulses, each pulse can have anywhere from 0 to an infinite number of photons, making the quantum state infinite-dimensional. That is, you would need an infinite number of rows and columns to write down the state as a matrix. This becomes a challenge when researchers are trying to study the security of these protocols quantitatively. It’s not possible to numerically optimize over these infinite-dimensional states, because computers only have a finite memory.

Upadhyaya, along with coauthors PhD student Jie Lin, postdoc Thomas van Himbeek, and Prof. Norbert Lütkenhaus, developed a dimension reduction method to solve this problem, which relates this infinite-dimensional scenario to a simpler finite one, making security analysis possible with existing numerical tools.



The team then applied their method to analyze a class of protocols called discrete-modulated continuous-variable QKD protocols, which are a strong candidate for use in large-scale quantum-secured networks. Crucially, they found that the solution to the reduced problem is close to the original infinite-dimensional one, meaning that almost nothing is lost during dimension reduction.



“We found a security proof that doesn’t rely on previous assumptions, but still gives as good a performance,” said Upadhyaya. “We also found that our method is like a faster, more generalizable version of another type of proof method which only applies to a restricted class of protocols.”

The researchers’ dimension reduction method is general, so Upadhyaya expects it will assist in analyzing other QKD protocols that might be useful for the quantum communication networks of the future. He also thinks they can extend the framework to explore other interesting questions in QKD, entanglement verification and quantum information more generally.

“One huge benefit of numerical tools is their flexibility. Things in the real world are never as clean as in homework problems. Devices are noisy, environments have disturbance and so on, but these things can be modelled. So, it’s nice that our method reduces infinite-dimensional problems to something our existing numerical tools can handle.” The implementation of the tools builds on the group’s numerical framework for key rate calculations, which is slated for an upcoming open-source release.

A future where large-scale quantum communication networks secure our most important information is one step closer, with analytical capabilities catching up to experimental capabilities.

NEW ALGORITHM USES A HOLOGRAM TO CONTROL TRAPPED IONS

Published in npj Quantum Information on April 8, 2021

<https://www.nature.com/articles/s41534-021-00396-0>

Researchers have discovered the most precise way to control individual ions using holographic optical engineering technology.

The new technology uses the first known holographic optical engineering device to control trapped ion qubits. This technology promises to help create more precise controls of qubits that will aid the development of quantum industry-specific hardware to further new quantum simulation experiments and potentially quantum error correction processes for trapped ion qubits.

“Our algorithm calculates the hologram’s profile and removes any aberrations from the light, which lets us develop a highly precise technique for programming ions,” says lead author Chung-You Shih, a PhD student at IQC.

Kazi Rajibul Islam, a faculty member at IQC and in physics and astronomy at Waterloo is the lead investigator on this work. His team has been trapping ions used in quantum simulation in the Laboratory for Quantum Information since 2019 but needed a precise way to control them.



A laser aimed at an ion can “talk” to it and change the quantum state of the ion, forming the building blocks of quantum information processing. However, laser beams have aberrations and distortions that can result in a messy, wide focus spot, which is a problem because the distance between trapped ions is a few micrometers — much narrower than a human hair.

The laser beam profiles the team wanted to stimulate the ions would need to be precisely engineered. To achieve this they took a laser, blew its light up to 1cm wide and then sent it through a digital micromirror device (DMD), which is programmable and functions as a movie projector. The DMD chip has two-million micron-scale mirrors on it that are individually controlled using electric voltage. Using an algorithm that Shih developed, the DMD chip is programmed to display a hologram pattern. The light produced from the DMD hologram can have its intensity and phase exactly controlled.

In testing, the team has been able to manipulate each ion with the holographic light. Previous research has struggled with cross talk, which means that if a laser focuses on one ion, the light leaks on the surrounding ions. With this device, the team successfully characterizes the aberrations using an ion as a sensor. They can then cancel the aberrations by adjusting the hologram and obtain the lowest cross talk in the world.

“There is a challenge in using commercially available DMD technology,” Shih says. “Its controller is made for projectors and UV lithography, not quantum experiments. Our next step is to develop our own hardware for quantum computation experiments.”

IQC RESEARCHERS OBSERVE UNPRECEDENTED HALL EFFECT

Published in Nature Communications on April 6, 2021
<https://www.nature.com/articles/s41467-021-22343-5>

Researchers studying two-dimensional crystalline materials have observed an electromagnetic effect, called the nonlinear anomalous Hall effect, of unprecedented size. Their finding opens the door to exploring other quantum materials using their techniques and hints at promising applications in spintronic devices.

“The nonlinear anomalous Hall effect could be found in other materials with low crystalline symmetry, but we cannot predict just how large of an effect we could expect,” said Wei Tsen, a faculty member at IQC and the University of Waterloo’s Department of Chemistry, the corresponding author on the paper. “So, this work opens the door to exploring other materials in a similar way.”

Understanding the different Hall effects

In 1879, Edwin Hall found that introducing a magnetic field perpendicular to electric current flowing through a conductor would cause an unexpected voltage drop along the third perpendicular, which we now understand as due to the electrons being deflected sideways by the magnetic field. This phenomenon came to be known as the Hall effect.



Later, he found that using a magnetic conductor produced an even larger Hall effect, which can persist even after removing the introduced magnetic field. This variation is now called the anomalous Hall effect (AHE).

“It’s tempting to think that this is just due to the internal magnetization of the sample,” said Tsen, “but it turns out that it actually has some deep quantum mechanical origins that people have only recently figured out.”

More recently, researchers have shown that materials with reduced crystal symmetries can generate a Hall effect with no sample magnetization or external magnetic field. Here, the electric current itself effectively magnetizes the material, and then that magnetization gives rise to the Hall effect. This unique property means that the size of the Hall effect increases quadratically with the size of the current, instead of linearly, and so is termed the nonlinear AHE.

Materials that maximize

The AHE has inspired researchers to see how large of an effect they can get with different materials when no magnetic field is applied. The larger the effect per a given input of current, the higher the Hall ratio. Materials with a high Hall ratio may prove useful for developing spintronic devices that use electric current to control spin.

Conventional magnetic conductors typically have a Hall ratio of about 0.01. Materials that exhibit a so-called giant AHE have a ratio of around 0.1. By taking advantage of the strong nonlinearity in molybdenum ditelluride and tungsten ditelluride, the researchers observed a Hall ratio of 2.47, more than an order of magnitude larger than previous records.

“It was exciting to see the manifestation of symmetry in the nonlinear AHE,” said Archana Tiwari, IQC and physics and astronomy department PhD student and first author on the paper.

“A lot of things came together to give rise to this large Hall ratio,” said Tsen. “The orientation in which we measured, the quality of the material, and the nonlinear mechanism itself all contributed.”

Many researchers also had to come together to make this experiment happen. The nonlinear AHE in the orientation and materials measured by Tiwari and Tsen was predicted by Binghai Yan of the Weizmann Institute of Science in Israel, also an author on the paper. The materials were grown by Tsen’s postdoctoral fellow Fangchu Chen and other collaborators while he was a PhD student at the Chinese Academy of Sciences. And researchers at the University of Michigan, Ann Arbor performed optical characterization of the samples.



Harnessing the Hall effect

Now that they have demonstrated the extremely large nonlinear AHE experimentally, Tsen hopes to continue exploring the effect's ties to other properties like electron spin. There are already hints that this connection exists, which means it could one day be useful for developing spintronic devices like magnetic random-access memory.

But we'll never know for sure unless we keep exploring. And that is just what Tsen and his team plan to do.

This research was supported by the Canada First Research Excellence Fund (CFREF) through Transformative Quantum Technologies (TQT) and by the Army Research Office.

COMBINING CLASSICAL AND QUANTUM COMPUTING OPENS DOOR TO NEW DISCOVERIES

Published in Physical Review Letters on June 1, 2021

<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.126.220501>

Researchers have discovered a new and more efficient computing method for pairing the reliability of a classical computer with the strength of a quantum system.

This new computing method opens the door to different algorithms and experiments that bring quantum researchers closer to near-term applications and discoveries of the technology.

“In the future, quantum computers could be used in a wide variety of applications including helping to remove carbon dioxide from the atmosphere, developing artificial limbs and designing more efficient pharmaceuticals,” said Christine Muschik, a principal investigator at IQC and a faculty member in physics and astronomy at the University of Waterloo.

The research team from IQC, in partnership with the University of Innsbruck, is the first to propose the measurement-based approach in a feedback loop with a regular computer, inventing a new way to tackle hard computing problems. Their method is resource-efficient and therefore can use small quantum states because they are custom-tailored to specific types of problems.

Hybrid computing, where a regular computer's processor and a quantum co-processor are paired into a feedback loop, gives researchers a more robust and flexible approach than trying to use a quantum computer alone.

While researchers are currently building hybrid, computers based on quantum gates, Muschik's research team was interested in the quantum computations that could be done without gates. They designed an algorithm in which a hybrid quantum-classical



computation is carried out by performing a sequence of measurements on an entangled quantum state.

The team's theoretical research is good news for quantum software developers and experimentalists because it provides a new way of thinking about optimization algorithms. The algorithm offers high error tolerance, often an issue in quantum systems, and works for a wide range of quantum systems, including photonic quantum co-processors.

Hybrid computing is a novel frontier in near-term quantum applications. By removing the reliance on quantum gates, Muschik and her team have removed the struggle with finicky and delicate resources and instead, by using entangled quantum states, they believe they will be able to design feedback loops that can be tailored to the datasets that the computers are researching in a more efficient manner.

“Quantum computers have the potential to solve problems that supercomputers can't, but they are still experimental and fragile,” said Muschik.

This project is funded by the Canadian Institute for Advanced Research (CIFAR).

NEW RESEARCH ENABLES NON-LINE-OF-SIGHT QUANTUM COMMUNICATIONS, IMAGING

Published in *Light: Science & Applications* on June 7, 2021

<https://www.nature.com/articles/s41377-021-00565-y>

Researchers have successfully transferred quantum coherence through photons scattered in free-space for the first time, enabling new research opportunities and applications in fields ranging from quantum communication to imaging and beyond.

“The ability to transfer quantum coherence via scattered photons means that now you can do many things that previously required direct line-of-sight free-space channels,” said Shihan Sajeed, lead author on the paper and a postdoctoral fellow at IQC and in the Department of Physics and Astronomy.

Normally, if you try to send and receive photons through the air (free-space) for quantum communication or any other quantum-encoded protocol, you need a direct line-of-sight between transmitter and receiver. Any objects—from as big as a wall to as small as a molecule—in the optical path will reflect some photons and scatter others, depending on how reflective the surface is.

Any quantum information encoded in the photons is typically lost in the scattered photons, interrupting the quantum channel.

Together with Thomas Jennewein, principal investigator of the Quantum Photonics lab at IQC, they found a way to encode quantum coherence in pairs of photon pulses sent



one after the other so that they would maintain their coherence even after scattering from a diffuse surface.

The researchers emitted two laser pulses with a different phase from each other that would interfere when combined—in other words, that were coherent. This quality of coherence is measured by visibility. The team placed detectors where they would only absorb scattered photons from the laser pulses, and observed a visibility of over 90%, meaning that they maintained their quantum coherence even after smashing against an object.

Their novel technique required custom hardware to make use of the coherent light they were generating. The single-photon-detector-array the team used to measure the returning light could detect one billion photons every second with a precision of 100 picoseconds. Only cutting-edge time-tagging electronics could handle the demands of this flow of light, and the team had to design their own electronics adapter board to communicate between the detectors and the computer that would process the data.

“Our technique can help image an object with quantum signals or transmit a quantum message in a noisy environment,” said Sajeed. “Scattered photons returning to our sensor will have a certain coherence, whereas noise in the environment will not, and so we can reject everything except the photons we originally sent.”

Sajeed expects their findings will stimulate new research and applications in quantum sensing, communication, and imaging in free space environments. The duo demonstrated quantum communication and imaging in their paper, but Sajeed said more research is needed to find out how their techniques could be used in various practical applications.

“We believe this could be used in quantum-enhanced Lidar (Light Detection and Ranging), quantum sensing, non-line-of-sight imaging, and many other areas—the possibilities are endless,” said Sajeed.

This work was supported by the National Research Council Canada, Defence Research Development Canada, Industry Canada, Canada Fund for Innovation, Ontario MRI, Ontario Research Fund, NSERC through the Discovery, CryptoWorks21, Strategic Partnership Grant programs, and the CFREF through TQT.

GROUNDBREAKING TECHNIQUE YIELDS IMPORTANT NEW DETAILS ON POSSIBLE ‘FIFTH FORCE’

Published in Science on September 9, 2021

<https://www.science.org/doi/10.1126/science.abc2794>

A group of researchers have used a groundbreaking new technique to reveal previously unrecognized properties of technologically crucial silicon crystals and uncovered new information about an important subatomic particle and a long-theorized fifth force of nature.



The research was an international collaboration conducted at the National Institute of Standards and Technology (NIST). Dmitry Pushin, a principal investigator at IQC and a faculty member in Waterloo's Department of Physics and Astronomy, was the only Canadian researcher involved in the study. Pushin was interested in producing high-quality quantum sensors out of perfect crystals.

By aiming subatomic particles known as neutrons at silicon crystals and monitoring the outcome with exquisite sensitivity, researchers were able to obtain three extraordinary results: the first measurement of a key neutron property in 20 years using a unique method; the highest-precision measurements of the effects of heat-related vibrations in a silicon crystal; and limits on the strength of a possible "fifth force" beyond standard physics theories.

In collaboration with researchers from Japan, the U.S. and Canada, the latest work resulted in a fourfold improvement in precision measurement of the silicon crystal structure factor.

Pushin, whose research specializes in neutron physics and interferometry, was instrumental in collecting neutron data and chemically etching samples, which led to examining unexplored forces beyond Standard Model.

"This was a multi-year experiment, and we had great results that are technically exciting and opens the door to future technologies," said Pushin.

The Standard Model is currently the widely accepted theory of how particles and forces interact at the smallest scales. But it's an incomplete explanation of how nature works, and scientists suspect there is more to the universe than the theory describes.

The Standard Model describes three fundamental forces in nature: electromagnetic, strong and weak nuclear force. Each force operates through the action of "carrier particles." For example, the photon is the force carrier for the electromagnetic force. But the Standard Model has yet to incorporate gravity in its description of nature. Furthermore, some experiments and theories suggest the possible presence of a fifth force.

The researchers are already planning more expansive pendellösung measurements using both silicon and germanium. They expect a possible factor of five reduction in their measurement uncertainties, which could produce the most precise measurement of the neutron charge radius to date and further constrain — or discover — a fifth force. They also plan to perform a cryogenic version of the experiment, which would lend insight into how the crystal atoms behave in their so-called "quantum ground state," which accounts for the fact that quantum objects are never perfectly still, even at temperatures approaching absolute zero.

This project is supported in part by the CFREF through the TQT programs.



Read more about the research from [NIST](#).

NEW RESEARCH OPENS THE BOOK ON ENTANGLED QUBITS

Published in Physical Review Letters on August 18, 2021

<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.127.080401>

Researchers have developed a new way to measure how quantum information behaves in correlated quantum systems that could be useful for understanding and improving quantum devices and quantum error correction codes.

“We are all excited about the potential of quantum entanglement for quantum information processing,” said Mohamad Niknam, who was a postdoctoral fellow at IQC when he co-authored the paper.

But to put [quantum entanglement](#) to use, researchers need to understand how quantum information behaves when it is encoded in an entangled state of the collection of qubits, known as a many-body quantum system.


Think of a 100-page book. By reading each page, you learn 1% of the content of the book. In the quantum entangled version of the same book, each page by itself does not have any comprehensible information, the information is encoded in the correlation between pages, and it is only after reading all the pages you learn everything in the book.

Entangled qubits in a quantum processor are similar. Looking at individual qubits doesn't reveal the quantum information, but looking at the correlations of the whole many-body system does. This fascinating feature of quantum systems has practical uses, in particular for quantum error correction. If quantum information is encoded in a highly entangled state, corruption of one of the qubits has a small effect on the integrity of the entire message.

“In this work, we introduced and implemented an experimental protocol for making collective observations of multi-qubit quantum states that reveals the volume of correlations. When applied to an entangled system, this method probes the length of the entangled state or essentially, the number of pages in the quantum entangled book,” said Niknam.

The team, which includes Lea Santos of Yeshiva University and IQC and University of Waterloo Department of Chemistry faculty member David Cory, call the new quantity the “correlation Renyi entropy.”

The researchers developed a protocol to measure this entropy using nuclear magnetic resonance techniques. They found that the correlation Renyi entropy captures information about the long-time dynamics of the quantum system that is usually not captured by existing entropies, such as entanglement entropy.



Providing a better understanding and quantification of the spread of quantum information, the researchers' new entropy will be a useful tool for scientists looking to measure and control the evolution of quantum systems in the devices that will power the next quantum revolution.

Niknam, now a postdoc at the Center for Quantum Science and Engineering at UCLA, said he enjoyed his time at IQC. "IQC allowed me the opportunity to contemplate fundamental problems in physics and explore them in the lab.

Now, he is excited to work at the intersection of theory and application designing new methods for efficient two-qubit gates and qubit entanglement, as well as quantum control applications.

This research was funded thanks in part to the CFREF.

HOT AND COLD: CONTROLLING NOISE IN A QUANTUM SATELLITE

Published in EPJ Quantum Technology on May 17, 2021

<https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-021-00103-0>

The quantum internet is one step closer to reality as researchers have demonstrated an effective regime for controlling noise in the photon detectors of a quantum satellite. "This experiment is an important demonstration of a crucial subsystem for the quantum satellite under the kind of conditions that the satellite will actually face in orbit," said Brendon Higgins, a Research Associate at IQC and the University of Waterloo Department of Physics and Astronomy, and the Science Team Technical Lead of the Quantum EncrYption and Science Satellite ([QEYSSat](#)).

The QEYSSat mission aims to launch Canada's first quantum satellite in early 2023 to serve as a technology demonstration for quantum satellite links. A quantum satellite network could secure our most precious data through the fundamental laws of quantum mechanics, using quantum key distribution (QKD).

To make the quantum internet possible, researchers need to be able to send photons carrying quantum information to satellites in orbit, and the satellites need single photon detectors that can receive the message. But proton radiation in space and the very nature of the detectors themselves often contribute to a kind of false positive noise called dark counts.

Combatting dark counts has been one of the key technical challenges the QEYSSat science team led by Thomas Jennewein, a faculty member at IQC and in the University of Waterloo Department of Physics and Astronomy, has been working to address. If they can limit dark counts, the detectors can do their job detecting real incoming quantum keys sent from ground stations on Earth.



The team set out to find the best approach to reduce dark counts and ensure their detectors can pick up a clean quantum signal. There are two main ways to combat dark counts: heating and cooling.

In a previous experiment, the team brought some photon detectors to the TRIUMF particle accelerator in Vancouver and bombarded them with the kind of proton radiation that they would face in space for set intervals of time. They kept the detectors as cool as possible without resorting to large, expensive cryostats that would be a logistical and financial challenge to launch into orbit and found that the lower temperature helped reduce dark counts to a nearly acceptable level.

To repair the damage done by the radiation and reduce the dark counts even further, the team then tried an approach called [annealing](#). Annealing is a process where a material is heated up just enough that the thermal energy helps work out any defects in it. They found that annealing got the dark counts down to the levels necessary to facilitate successful quantum key distribution.

“However, the fact is these detectors will be orbiting in space and continually accumulating proton radiation and the corresponding defects,” said Higgins. “So the key question is: when do you decide to perform the annealing?”

That is what the team set out to discover in their latest publication in EPJ Quantum Technology.

As the satellite bearing the detectors orbits the Earth, it will need to connect with ground stations it passes at certain times, and at other times it will be just travelling. What the team wanted to find out was whether the dark counts were kept under control best by annealing at set periods during the satellite’s orbit, or if the annealing should only take place once the dark counts reach a certain threshold. They also wanted to know if the repetitive exposure to radiation would make the dark counts unmanageable.

To find out, the researchers needed a much more complicated experiment that allowed them to cool the detectors and irradiate them, and then anneal them, and then cool and irradiate them again, repeatedly, better simulating actual operation in orbit.

“We found that we were able to keep the dark counts below the threshold we need to achieve to support the QKD protocol we want to use,” said Higgins.

And they also found that whether they annealed on a set schedule or based on the incidence of dark counts didn’t make a significant difference, so for the actual QEYSSat launch, they will err on the side of caution and only anneal when the dark counts exceed a predefined threshold.

There is still much work to be done before Canada launches its first satellite for quantum communication in 2023, but these latest results are an important step towards a functioning quantum internet.



SIMULATING QUANTUM PARTICLES ON A LATTICE

Published in Physical Review Letters on September 2, 2021

<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.127.100503>

A team of researchers at IQC have developed a new quantum simulator that uses microwave photons in a superconducting cavity to simulate particles on a lattice similar to those found in superconductors or atomic nuclei.

“There is a particular interest in performing quantum simulations of systems that cannot be simulated using even the most powerful classical supercomputers,” said Christopher Wilson, a faculty member at IQC and the Department of Electrical and Computer Engineering at the University of Waterloo. “While very powerful classical simulation tools exist, many important problems remain intractable. Here, we present a programmable platform using superconducting quantum circuits. We use it for a small-scale simulation of the bosonic Creutz ladder, an important historical model which exhibits a wide range of interesting behavior including topological and edge states.”

A quantum simulator is a limited-use quantum computer: a machine that can be programmed to replicate the behavior of a specific quantum system that is too complex to simulate using classical methods. Because of their comparative simplicity, many researchers believe that quantum simulators could deliver useful applications sooner than universal quantum computers will. With this goal in mind, Wilson along with his colleagues have used a chip-based superconducting cavity to build a quantum simulator that can simulate quantum particles on a lattice. Such particle-lattice systems can be used as models for the behavior of high-temperature superconductors or the particles inside an atomic nucleus.

The superconducting cavity holds microwave radiation of specific frequencies, or modes, which are determined by the cavity’s size. The researchers change the effective size of the cavity by delaying the propagation of photons at one end by a variable interval. When the cavity contains multiple microwave photons, tuning its effective length causes the various cavity modes to interact with each other.

The team used this setup to create a so-called bosonic Creutz ladder—a simple model of particles moving on a lattice of four nodes. In their implementation of the model, Wilson and colleagues engineered the cavity-mode interactions so that each mode of the cavity corresponded to a node on the lattice. They also showed that the quantum simulator can be programmed *in situ* by introducing microwaves of different frequencies into the cavity. The technique can be scaled up to simulate more complex quantum systems by placing multiple superconducting cavities on the chip.

The team hopes to quickly scale up the size of their simulations and try to test new models. They expect that the inherent programmability of the platform should make progress easier than for dedicated simulators design to simulate a single model.



Original synopsis by Sophia Chen for [Physical Review Letters](#).

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This project is supported in part by the CFREF through the TQT program.

UNLOCKING HIGH-DIMENSIONAL QUANTUM OPTICS

Published on November 22, 2021 in Physical Review A

<https://journals.aps.org/prapdf/10.1103/PhysRevA.104.L051701>

Collaboration is key at IQC. IQC researchers are working together towards unlocking high-dimensional quantum optics. They are advancing fundamental research with future applications for quantum communications and computing. Building off earlier research, a group of IQC researchers measured the correlation of polarization-entangled photon pairs using orbital angular momentum (OAM) lattices.

OAM, a property of light, refers to the twisting of a particle. The polarization of light offers access to only a limited number of states, but OAM allows access a vast number of states. The team used both polarization and OAM to combine the advantages of both. Expanding the number of accessible states with OAM, while using the controllable nature of polarization, moves the research towards one of the big goals of quantum optics: high-dimensional entanglement.

A. R. Cameron et al., “Remote state preparation of single-photon orbital-angular-momentum lattices,” *Phys. Rev. A* **104**, L051701 (2021).

An [earlier study led by Dusan Sarenac](#), a research associate at IQC, investigated OAM lattices with neutrons. Following the success of that first experiment with neutrons, the team posited that the same may also be measured with photons.

“On the surface, neutrons and photons don't seem to have a lot in common, but when you dig in, they do. Sometimes the applications of one end up being interesting for the other as well,” said Andrew Cameron, PhD student with the Department of Physics and Astronomy and IQC member.

The IQC advantage is that theorists and experimentalists work together. It is a collaborative and interdisciplinary approach to research. Each researcher brought their unique expertise to each step of the experiment from design to implementation in the Quantum Optics and Quantum Information lab.

This team first demonstrated a Talbot effect of OAM lattices with single photons. This latest investigation introduces multi-particle entanglement, not yet possible with neutrons.

“We published our first report about what happens if these kind of lattice states propagate. They transform and interfere with themselves as they propagate which is called the Talbot effect,” said Cameron. “The second step was applying the lattice



transformation to one of the photons to produce correlations between the OAM of one photon and the polarization of its entangled partner.”

Entanglement is when two objects or particles have such a strong correlation that the properties of one cannot be described without considering the properties of other. Using photon pairs with polarization entanglement, the team passed one photon from each pair through a prism to manipulate its OAM. The team then measured the polarization of one entangled photon to determine the OAM lattice of its photon partner. The experiment showed a strong correlation between photon pairs, indicating entanglement.

Future work is to study the lattices with more prism pairs to expand the number of accessible OAM states. Unlocking high-dimensional quantum optics would expand quantum communication protocols to be more robust and encode more information.

Kevin Resch, principal investigator led this research in collaboration with IQC’s TQT led by professor David Cory. This research was supported in part by the CFREF through TQT.

COMBATING CROSSTALK IN QUANTUM COMPUTERS

Published in PRX Quantum on October 20, 2021

<https://journals.aps.org/prxquantum/pdf/10.1103/PRXQuantum.2.040313>

In an advance towards better control over large quantum computers, researchers have demonstrated a new tool to compensate for crosstalk in superconducting circuits.

“Ultimately, if we want to be able to build very large quantum computers, we’re going to need to keep errors to manageable levels,” said IQC and University of Waterloo Department of Physics and Astronomy faculty member Adrian Lupascu. “What we did in this paper was to tackle one point where errors creep in, which has to do with control signals.”

A superconducting chip can have many qubits—the quantum version of your classical computer bit—and scientists need to be able to send an electrical or magnetic signal to each one to control them individually.

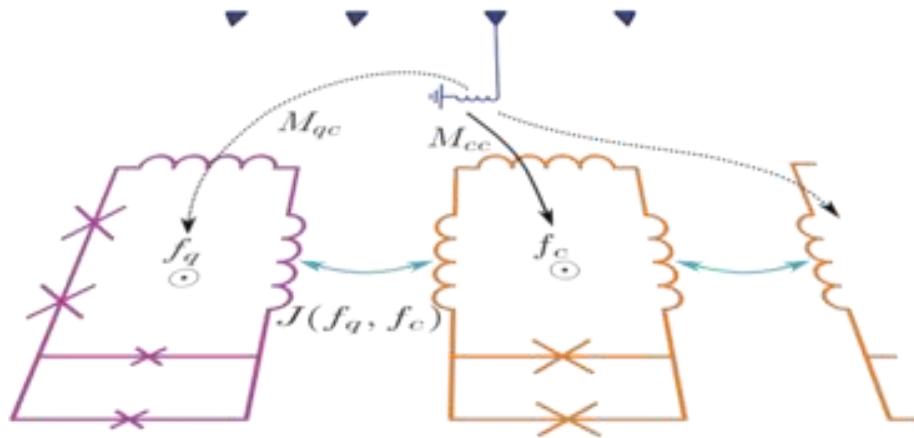
Independent control is not so easy to maintain, however. With so many control lines so close together on the same chip, parts of signals get ‘borrowed’ by qubits they weren’t meant for, and the result is a noisy mess. This pollution is called crosstalk.

The ideal approach to dealing with crosstalk is to design your device so it doesn’t happen in the first place. But this easier said than done, and not always possible depending on the type of device you’re using.

The alternative approach is to compensate for the crosstalk. If qubit one is getting too much signal because it is being affected by the signal to qubit two, you can alter the level of signal going to each qubit to compensate. But there’s a problem: to compensate, you

need to have a very accurate understanding of the crosstalk that's happening. Large quantum systems are too complicated to simulate, which is part of the reason why they have the potential to be so powerful. But it also means it is difficult to model all their dynamics.

The researchers found another way. They created a fully automated tool that takes advantage of a known fundamental property of superconducting circuits to start with a rough estimate of crosstalk and iterates repeatedly until it has a very accurate characterization.



Coupling from the electric control signal (blue) to superconducting circuits (purple and orange). The solid black arrow indicates coupling to the intended loop and the dashed arrow indicates crosstalk to unintended loops. The teal arrow indicates interaction between circuit elements, which hampers crosstalk calibration measurement.

Importantly, the team demonstrated the tool on a device that is one of the largest quantum computers currently in operation, in terms of number of independent control signals, showing promising applications in the ever-growing systems of the future. And because it takes advantage of a fundamental property of superconducting systems, it is device-independent within that set of systems, meaning the specific design of a device is not a barrier to using this tool.

The team also developed a method to quantify the error in their tool's procedure, letting them know how close they are to determining the actual crosstalk. So far, the results are promising; the error rates are well within the normal range for potentially achieving scalable quantum information processing.

The breakthrough was the result of a program in quantum annealing involving an international collaboration of more than ten partners across academia, government and industry, including MIT Lincoln Laboratory in Massachusetts, where much of the experimental work took place.



“I would say it is the most sophisticated data analysis tool that I have been involved with: being able to process so much data in a way that will be reliable without any human intervention, essentially—that is something that was very interesting to see,” said Lupascu.

First author Xi Dai, a PhD student at IQC and the Department of Physics and Astronomy, played a crucial role in making the breakthrough happen.

“Many implementations of quantum computing rely on electric control to manipulate qubits, and crosstalk is a major challenge to scaling up quantum computers,” said Dai. “We proposed an innovative crosstalk calibration procedure that is automated and implemented on superconducting devices with up to 27 control loops, which are among the largest in the community.”

The researchers’ work is another piece in the puzzle of a large, powerful quantum computer that do things totally impossible for a classical computer.

“If you want to build a meaningful quantum computer, you have to put many qubits together and maintain low error rates,” said Lupascu. “This will likely require a combination of fundamentally new science and major technical developments.”

The ultimate answer may be unclear, but compensating for crosstalk is a small but meaningful step towards a solution.

BRIDGING THEORY TO EXPERIMENTAL REALITY

Published in npj Quantum on January 27, 2022

<https://rdcu.be/cGexB>

A duo of researchers, including IQC PhD candidate Shayan Majidy, developed a mathematical tool to investigate quantum thermodynamics on existing quantum hardware. This research helps the efforts underway to bridge the gap between theory and experimental reality.

The field of thermodynamics describes how energy is exchanged in the forms of heat and work. Classically, this area of study focuses on large systems.

If we look at a steaming cup of coffee left sitting on the table, eventually it cools down. It does this by transferring heat to its environment. Heat is an example of a “charge.” A charge is a quantity that can move around locally but is conserved globally.

Quantum thermodynamics considers systems on the atomic scale and accounts for quantum effects. In quantum mechanics, charges may not *commute*. This means that if we know something about one charge, it’s possible that we can’t know something about the other. In the example of the coffee cup, a quantum coffee cup can exchange noncommuting charges. If we know how much the coffee cup cools down over time, we



couldn't know, for example, what happens to the coffee particles that evaporate into the environment.

Studying noncommuting charges has resulted in several new theoretical discoveries in quantum thermodynamics. Now, there is a procedure to help bridge these discoveries to experimental reality.

Shayan Majidy, a Vanier scholar and PhD candidate at IQC and the Department of Physics and Astronomy at the University of Waterloo, with Nicole Yunger Halpern, a University of Maryland researcher, created a procedure for building a Hamiltonian—a mathematical function that describes how a system changes or evolves over time—for a system of noncommuting charges.

This new method allows the design of physical experiments to test theoretical results that have been proposed in quantum thermodynamics—to find out what physically happens to the quantum cup of coffee after it exchanges charges with its environment.

“We've formulated this procedure for building Hamiltonians that move noncommuting charges,” said Majidy. “It's exciting because Hamiltonians are the language of experimentalists. Our hope is that someone can use our results to test the theoretical results in quantum thermodynamics in the lab on existing quantum processing platforms like trapped ions, cold atoms, superconductors or nuclear magnetic resonance.”

Putting noncommuting quantum thermodynamics to the test could result in interesting revelations. “Quantum effects have propelled diverse fields to achieve once unthinkable feats. Examples of this include generating images of internal organs and the abundant applications of laser-based technologies,” Majidy explained. “It's exciting to think about what could be achieved when applying quantum mechanics to thermodynamics.”

So far, there are some intriguing possibilities for the application of noncommuting charges to quantum technologies. More efficient quantum heat engines and longer lasting quantum memories might be some of the possible applications on the horizon.

Read more about this work in the Quantum Frontiers blog post by Majidy: [Building a Koi pond with Lie algebras](#).

CANADIAN RESEARCHERS ACHIEVE FIRST QUANTUM SIMULATION OF BARYONS

Published in Nature Communications on November 11, 2021

<https://www.nature.com/articles/s41467-021-26825-4>

A team of researchers led by IQC faculty member performed the first-ever simulation of baryons—fundamental quantum particles—on a quantum computer.



With their results, the team has taken a step towards more complex quantum simulations that will allow scientists to study neutron stars, learn more about the earliest moments of the universe, and realize the revolutionary potential of quantum computers.

“This is an important step forward – it is the first simulation of baryons on a quantum computer ever,” IQC faculty member Christine Muschik said. “Instead of smashing particles in an accelerator, a quantum computer may one day allow us to simulate these interactions that we use to study the origins of the universe and so much more.”

Muschik, also a physics and astronomy professor at the University of Waterloo and associate faculty member at Perimeter Institute, leads the [Quantum Interactions Group](#), which studies the quantum simulation of lattice gauge theories. These theories are descriptions of the physics of reality, including the Standard Model of particle physics. The more inclusive a gauge theory is of fields, forces, particles, spatial dimensions and other parameters, the more complex it is—and the more difficult it is for a classical supercomputer to model.

Non-Abelian gauge theories are particularly interesting candidates for simulations because they are responsible for the stability of matter as we know it. Classical computers can simulate the non-Abelian matter described in these theories, but there are important situations—such as matter with high densities—that are inaccessible for regular computers. And while the ability to describe and simulate non-Abelian matter is fundamental for being able to describe our universe, none has ever been simulated on a quantum computer.

Working with Randy Lewis from York University, Muschik’s team at IQC developed a resource-efficient quantum algorithm that allowed them to simulate a system within a simple non-Abelian gauge theory on IBM’s cloud quantum computer paired with a classical computer.

With this landmark step, the researchers are blazing a trail towards the quantum simulation of gauge theories far beyond the capabilities and resources of even the most powerful supercomputers in the world.

“What’s exciting about these results for us is that the theory can be made so much more complicated,” Jinglei Zhang, a postdoctoral fellow at IQC and the University of Waterloo Department of Physics and Astronomy said. “We can consider simulating matter at higher densities, which is beyond the capability of classical computers.”

As scientists develop more powerful quantum computers and quantum algorithms, they will be able to simulate the physics of these more complex non-Abelian gauge theories and study fascinating phenomena beyond the reach of our best supercomputers.

This breakthrough demonstration is an important step towards a new era of understanding the universe based on quantum simulation.



This research was funded in part by the Canadian Institute for Advanced Research as well as the CFREF through TQT.

Watch [The first quantum simulation of baryons](#) for a visual breakdown of the new results.

FINETUNING CHEMISTRY BY QUANTUM INTERFERENCE

Published in Science on March 3, 2022

<https://www.science.org/doi/10.1126/science.abl7257>

Atoms and molecules are the building blocks of chemistry and are important to our understanding of the world. By cooling atoms and molecules to ultracold temperatures it opens up a new understanding of quantum chemistry. Working with nanokelvin temperatures, one billion times colder than Antarctica during winter, researchers can observe and control particles in ways not possible at room temperature. When really cold, particles behave in strange and exciting ways. Researchers are discovering unexpected results by looking at particles from a quantum perspective.


New research by Alan Jamison, IQC and Department of Physics and Astronomy faculty member at the University of Waterloo, in collaboration with the MIT-Harvard Center for Ultracold Atoms, has demonstrated magnetic control of chemical reactions by quantum interference. The team successfully finetuned chemical reactions between an atom and a molecule to advance new insights for future applications in chemistry.

In the lab, the researchers cooled sodium atoms and sodium-lithium molecules. The ultracold temperature creates an environment where the particles slow down and are easier to observe. Researchers can then use quantum states to control the particles.

By studying chemical reactions in specific quantum states, we can learn how an effect like interference can direct reactions. Particles must collide at short range for a chemical reaction to occur, but at ultracold temperatures, particles usually reflect away at longer distances. When a reaction is guaranteed to happen every time the particles collide at short range, the reaction rate can be calculated and is referred to as the “universal limit.”

Surprisingly, when a reaction is unlikely to happen at short range, it becomes possible to tune the reaction rate to be faster than the universal limit. This becomes possible through [quantum interference](#). In the quantum world, particles behave like waves and can have constructive or destructive interference depending on whether the waves build off each other or cancel each other out.

If two particles can collide at short range and move apart again without reacting, the returning part of the wavefunction can interfere with the part of the wavefunction that reflected at long range, cancelling some of it out. If the collision can be tuned just right, this destructive interference at long distances becomes strong, and the particles collide at short range much more often.



The team demonstrated, for the first time, the ability to modify the reaction rate from far below the universal limit to far above. Using a Feshbach resonance, they were able to tune this destructive interference to demonstrate control of chemical reactions. Feshbach resonances occur when two or more particles collide and are bound together for a short period of time, allowing researchers to modify how collisions occur.

“We can tune the chemical reaction rate and try to get an intuitive sense of what’s going on with these reactions,” said Jamison. “With a Feshbach resonance we can measure in either direction, to slow reactions down or speed them up.”

You can think of this like tuning a radio dial. If you tune it just right, you can hear your favourite station but if you tune it elsewhere, you will hear static. The Feshbach resonance allowed the team to finetune and direct the reactions between the atoms and molecules. They tuned the resonance between a point where a reaction was unlikely to occur to a point where reactions were very likely.

Quantum control of chemistry is unlocking exciting streams of fundamental research with new directions for researchers to explore.

“From a physicist’s perspective, chemistry is complicated. We each have our own tools to understand our own fields of study. When we approach chemistry from a physics perspective we can explore and discover new fundamental insights,” said Jamison.


Recruitment – Faculty

Alongside research and training, each year IQC prioritizes recruitment activities to continue to attract world-class theoretical and experimental researchers across a range of disciplines. Currently home to 31 faculty members who work in teams to pursue challenging problems in scaling complex quantum systems, this fiscal year IQC welcomed one new faculty member to its research community.



Shalev Ben-David joined the David R. Cheriton School of Computer Science as an Assistant Professor in July 2018. Previously, he was a Hartree Postdoctoral Fellow at the University of Maryland, College Park. In 2017, Shalev received his PhD in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology, supervised by Scott Aaronson. In January 2022, Ben-David became a faculty member at IQC to pursue his research interests in classical and quantum complexity theory.

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



existing faculty. In addition to adding a faculty member in 2021-22, IQC suffered for its own success when Dr. Joel Wallman left IQC to continue with Keysight Technologies which acquired the company he founded with Dr. Joseph Emerson, Quantum Benchmark. Additionally, as the first-of-its-kind academic institute (celebrating its 20th anniversary in 2022) dedicated to quantum science and technology, IQC saw the retirement of Dr. Vern Paulsen in fiscal 2021-2022, though it is worth noting that both members continue as associates with IQC.

Recruitment – Research Associates

In the face of changing and divergent travel restrictions due to the ongoing pandemic, IQC had a very successful year recruiting national and international research associates, as well as recruiting from the existing cohort of IQC postdoctoral fellows and recently completed doctoral students. Out of a total of 20 Research Associates currently part of the IQC complement, 10 were hired in 2021-2022 and include hires from Germany, Ukraine, Brazil and USA. Another 3 of the 10 new Research Associates are former IQC postdoctoral fellows or graduate students, which is a testament to the excellent graduate programs IQC has developed over the last 20 years. These research associates work with IQC principal investigators to advance research programs and initiatives. A full list of all IQC contributors in 2021-2022 including 31 faculty members, 2 research assistant professors, and 27 research associates can be found in Appendix C beginning on page 79.



Awards & Research Chairs

IQC researchers have collectively been awarded \$29,784,391 in research funding during the period of April 1, 2021, to March 31, 2022. Funding sources are diverse and include research chair awards, funding from the Government of Canada, the Canada Foundation for Innovation (CFI), industry partners and others.

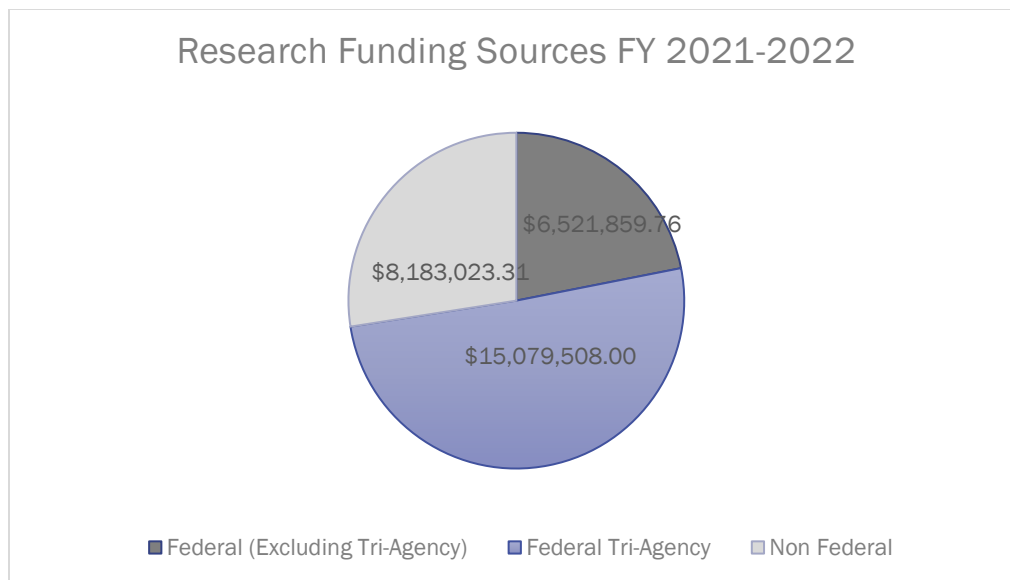


Figure 1: Non Federal includes previous 'Other' category.

The calibre of quantum information research by IQC faculty members continues to make a global impact. The quality and ability of these members is evidenced not only by their research, but also by the many awards and acknowledgements they receive. In a globally competitive field, such awards reinforce IQC and Canada’s excellent talent in quantum information. Below is a list of prominent awards faculty members received in 2021-2022:

Faculty Member	Award Sponsor
Adam Wei Tsen	CFREF (Canada First Research Excellence Fund)
	ISED (Innovation, Science and Economic Development Canada)
	Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award)
	NSERC - Discovery Grants - Individual (RGPIN)
Adrian Lupascu	US Army Research Office
	Massachusetts Institute of Technology
	NSERC - Discovery Grants - Individual (RGPIN)
	University of Southern California
	UW - NSERC - GRF

Alan Jamison	NSERC - Discovery Grants - Discovery Launch Supplement (DGECR) NSERC - Discovery Grants - Individual (RGPIN)
Christine Muschik	NSERC - Discovery Grants - Individual (RGPIN)
Christopher Wilson	CFI - IOF (Infrastructure Operating Fund) NSERC - Discovery Grants - DND Supplement NSERC - Discovery Grants - Individual (RGPIN)
Crystal Senko	CRC - NSERC ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
David Cory	CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
David Gosset	CIFAR (Canadian Institute for Advanced Research) IBM US ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Accelerator Supplement (RGPAS) NSERC - Discovery Grants - Individual (RGPIN)
Debbie Leung	NSERC - Discovery Grants - Individual (RGPIN)
Dmitry Pushin	ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
Guo-Xing Miao	CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN)
John Watrous	Canadian Institute for Advanced Research CFREF (Canada First Research Excellence Fund) NSERC - Discovery Grants - Individual (RGPIN)
Jon Yard	ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
Jonathan Baugh	CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) NRC - Other



	NSERC - Discovery Grants - Individual (RGPIN) PWGSC - Other
Joseph Emerson	NSERC - Discovery Grants - Individual (RGPIN) University of Innsbruck
Kazi Rajibul Islam	ISED (Innovation, Science and Economic Development Canada) Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN)
Kevin Resch	CIHR - Personnel Award CRC - NSERC ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
Kyung Soo Choi	NSERC - Discovery Grants - Individual (RGPIN)
Matteo Mariantoni	CFI - IOF (Infrastructure Operating Fund) ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Accelerator Supplement (RGPAS) NSERC - Discovery Grants - Individual (RGPIN)
Michael Reimer	CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award) NSERC - Discovery Grants - Individual (RGPIN) PWGSC - Other Single Quantum Systems Inc
Michal Bajcsy	BioGraph Sense CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award)
Michele Mosca	Crypto4A Technologies ISED (Innovation, Science and Economic Development Canada) JPMorgan Chase and Co Massachusetts Institute of Technology Mitacs Inc NSERC - Alliance Grants



	<p>NSERC - Discovery Grants - Individual (RGPIN) NSERC - I2I (Idea to Innovation Program) PWGSC - Other Qeynet Inc Rhea Group (Canada) University of Montreal UW - CPI (Cybersecurity and Privacy Institute)</p>
Na Young Kim	<p>CFREF (Canada First Research Excellence Fund) ISED (Innovation, Science and Economic Development Canada) Ministry of Colleges & Universities (MCU) - ERA (Early Researcher Award) Ministry of Colleges & Universities (MCU) - ORF-RE (Ontario Research Fund - Research Excellence) NSERC - Discovery Grants - Individual (RGPIN) NSERC - Research Tools and Instruments Grants (RTI) Category 1</p>
Norbert Lütkenhaus	<p>Honeywell International Inc ISED (Innovation, Science and Economic Development Canada) NSERC - Alliance Grants NSERC - Discovery Grants - Individual (RGPIN) NSERC - Miscellaneous</p>
Raffi Budakian	<p>ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN) NSERC - Research Tools and Instruments Grants (RTI) Category 1</p>
Raymond Laflamme	<p>CRC - NSERC ISED (Innovation, Science and Economic Development Canada) Keysight Technologies Inc NSERC - Alliance Grants NSERC - Discovery Grants - Individual (RGPIN) Perimeter Institute for Theoretical Physics</p>
Richard Cleve	<p>NSERC - Discovery Grants - Individual (RGPIN)</p>
Shalev Ben-David	<p>NSERC - Discovery Grants - Individual (RGPIN)</p>
Thomas Jennewein	<p>Canadian Space Agency CFI - IOF (Infrastructure Operating Fund) CFREF (Canada First Research Excellence Fund) Honeywell International Inc</p>

	ISED (Innovation, Science and Economic Development Canada) NRC - Other NSERC - Alliance Grants NSERC - Discovery Grants - DND Supplement NSERC - Discovery Grants - Individual (RGPIN) Qeynet Inc
Vern Paulsen	ISED (Innovation, Science and Economic Development Canada) NSERC - Discovery Grants - Individual (RGPIN)
William Slofstra	Alfred P Sloan Foundation NSERC - Discovery Grants - Individual (RGPIN)

NB: This list is not exhaustive.

IQC is also home to the following Research Chairs:

- Crystal Senko, Canada Research Chair (2020-2025)
- Raymond Laflamme, Mike and Ophelia Lazaridis Chair(2017-2027)
- David Cory, Canada Excellence Research Chair Laureate (2017)
- Debbie Leung, University Research Chair (2015-2022)
- Kevin Resch, Canada Research Chair (2013-2023)
- Raffi Budakian, University of Waterloo Endowed Chair in Nanotechnology (2014-ongoing)
- Michele Mosca, University Research Chair (2012-2022)
- Christine Muschik, University Research Chair (2022-2027)
- William Slofstra, University Research Chair (2022-2027)
- Raymond Laflamme, Canada Research Chair (2002-2022)



Infrastructure – Mike & Ophelia Lazaridis Quantum-Nano Centre

As of March 2022, there are 16 operational research labs in the Lazaridis Centre, with an additional research lab currently being finished for Alan Jamison.

Selected labs are listed below :

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

In addition to the building of new labs, IQC continues to improve the quality of our existing infrastructure. For example, the Quantum Outreach Lab has been upgraded with a virtual recording studio to engage students and audiences with live presentations, including visual demonstrations and a lightboard. To support the lab's development of resource kits for students and teachers, a dedicated 3D printer has also been installed. In 2021-2022, the Quantum Outreach lab developed affordable educational demonstration kits to teach quantum key distribution, which were sent to 80 high school teachers in Canada and the United States. The lab was also able to live-stream experiments aimed at engaging participants remotely, and collectively taught key quantum concepts to over 400 people this year.

The Quantum Outreach Lab is continuing to build more experiments that can be run with remote participants, and is in the process of developing a new online learning platform: Quantum Online Learning Library (QuOLL). This work contributes to the creation of a rich environment that will allow Canada to maintain a strong standing in quantum research into the future.

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

QNFCF is responsible for three labs in the Quantum-Nano Centre's Metrology area: TEM lab, FIB lab and Dry Sample Prep lab. Open to researchers in government, industry and academia, over the past year the QNFCF reported a total of 31,259 hours of independent lab equipment use logged by registered lab users. This usage rate is very comparable to 2019-20 when IQC reported 32,894 hours of usage by registered users (-5% versus 2019-2020 in the context of a ~20% decrease in available hours), despite restricted hours from April to September of 2021. Academic and industrial demand for



lab time continues to draw significant interest from groups across Ontario and Canada.

- Lab operations returned to 112 hrs/week on September 13, 2021 (versus 60 hrs/week from April through August).
- The total number of users has increased to 209 (from 195 in 2019-20), including 39 users from industry and 8 that work in both industry and academia.
- 77 research groups used QNFCF facilities (60 Academic, 17 Industry), which points to a growing demand for advanced laboratory facilities in Canada.
- 23 total institutions (6 Academic and 17 Industry groups) use the facilities at QNFCF. This includes universities from as far as Prince Edward Island and Alberta.
- 1000+ hours of hands-on equipment user training; this training has a cascading effect on the amount of highly skilled labour hours available across Canada, (i.e. training a group from the University of Prince Edward Island, for example, increases expertise across the country).
- 2700+ hours of process development activities resulted in the creation and characterization of multiple new processes and new technical reports to the benefit all registered users.

IQC supports the QNFCF operations by contributing to staff salaries, equipment acquisitions and equipment service contracts. In the 2021-2022 Fiscal Year IQC contributed \$232,500 to operations at QNFCF.

Infrastructure – Research Advancement Centres (RAC)

As of March 31, 2022, there are 7 operational research labs in RAC (I and II), 6 of which are led by a Principal Investigator:

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

While the Quantum Exploration Space does not have a principal investigator, this impressive lab space supports students enrolled in the new MSc Physics (Quantum Technology) program, offered at Waterloo in partnership with IQC and TQT. Two of the three lab-based courses required to complete the Quantum Technology degree are held



in this lab and, soon all three lab requirements will be hosted there. This lab is used to give students and visitors access to real, research-grade quantum systems for laboratory experiments and knowledge building. High school and undergraduate students in programs such as Quantum School for Young Students (QSYS) and Undergraduate School on Experimental Quantum Information Processing (USEQIP) also benefit from detailed, hands-on experience with real systems. In the future, the lab will allow large numbers of industry experts and visitors to witness quantum devices in action.

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

Collaborations & Seeking New Partnerships


The IQC research community values opportunities for collaboration, both with other research groups and universities as well as with government, non-profits and private organizations. In 2021-2022, IQC faculty members collectively reported 179 active collaborations with 134 unique organizations that span the globe. The following list of organizations includes examples of such organizations and includes universities, research institutes, private corporations, and government. A full list of collaborations can be found in Appendix D on page 81.

- Qubic
- Honeywell
- National Research Council of Canada
- Canadian Space Agency
- Crypto4A Technologies
- National Institute of Optics, Canada
- Massachusetts Institute of Technology
- CERN
- SERENE-RISC
- University of British Columbia
- DARPA
- Tsinghua University
- Rhea Group Canada
- Perimeter Institute of Theoretical Physics
- University of Maryland
- Mitacs
- Sandia National Labs
- Jet Propulsion Laboratory
- Columbia University
- Institute for Quantum Optics and Quantum Information (IQOQI)
- McGill University
- Institut Quantique
- Centre for Quantum Technologies
- Weizmann Institute of Science
- University of Michigan
- University of Calgary



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

- Meetings between IQC and the Office of the Chief Scientist at Natural Resources Canada (NRCan) continue, centred on discussions about how IQC's current and future research may have applications in the natural resources sector. As the natural resources sector is well-positioned to be an early adopter of quantum technologies, these discussions identified potential collaboration areas. This partnership is expected to be ongoing at the researcher-to-researcher level as well as at leadership levels to facilitate broad integration of quantum research. IQC also hosted tours for various provincial and federal members of parliament including Ontario Minister of Colleges and Universities, Jill Dunlop in September of 2021.
- At the March meeting of the American Physical Society, Senior Scientific Outreach Manager, John Donohue delivered a presentation focusing on IQC's role in developing a Canadian quantum workforce via outreach to high school students and support for high school science teachers. The long running Quantum School for Young Students (formerly Quantum Cryptography School for Young Students [QSYS]) introduces high school students to quantum information science as they are making decisions about their college and university careers. IQC also supports high school science teachers via Schrödinger's Class, a workshop that introduces high school teachers to quantum topics and provides hands-on-activities and labs designed to teach key quantum topics at the high school level. This dual track approach to developing interest in advanced quantum science topics and simultaneously supporting the teaching of quantum science has created an environment where dozens of QSYS participants have continued on to graduate STEM careers at the University of Waterloo.
- IQC executive directors participated in meetings with Tata Consultancy Services and Foxconn at the University of Waterloo in 2021 and early 2022. These meetings provided opportunities to showcase the world-class research and talent developing in the Waterloo Region and have the potential to attract national and international corporations to the region and Canada. Historically, Waterloo has developed such a sizable talent pool that companies like Google have found it more cost-effective to begin operating in Waterloo Region, than to move all the talent from Waterloo to a different location. IQC is continuing to draw cutting-edge companies to the region.
- Faculty members David Gosset and Michele Mosca provided advisory guidance for the setup of the NRC Applied Quantum Computing Challenge via the "Program focus working group, NRC Applied Quantum Computing Challenge Program." Faculty continue to work with government agencies behind the scenes



to provide expert guidance on the formation of the National Quantum Strategy and the mechanisms to fund Canadian quantum development.

- The Waterloo EDC facilitated IQC tours for Volkswagen and the Japanese Consul General to provide wider industrial and international exposure for the groundbreaking work being pursued at IQC.



Objective B

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

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

Planned Activities:

- Continuing to grow and attract the best talent to IQC's graduate program
- Supporting the new MSc Physics (Quantum Technology) program to provide students with hands-on learning on quantum platforms and to produce students capable of driving growth in new quantum industries
- Fielding at least 400 applications to the University of Waterloo/IQC graduate studies program
- Expanding connections made with undergraduate programs at Ontario and Canadian universities
- Continuing to host timely, focused conferences, workshops, seminars and courses as pandemic-related logistical restrictions are reduced
- Hosting up to 10 virtual workshops and seminars
- Jointly sponsor up to 10 workshops and conferences with national and international partner organizations

Attracting Talent – Postdoctoral Fellows

Postdoctoral fellowship positions provide young scientists with invaluable opportunities for additional mentoring, publishing, researching and teaching . In 2021-22, IQC recruited 12 new postdoctoral fellows, two of whom recently completed their doctoral studies at IQC. This ability to recruit internally is due to the strength of the IQC graduate program that has allowed IQC to continue world-class research and provide our recent graduates with the opportunity to take the next step in their careers, even while faced with significant travel restrictions.

Over the last fiscal year, IQC employed a total of 70 Postdoctoral Fellows, 22 of which were women (31%). As outlined in the table below, newly recruited fellows came from prominent institutions in Canada and around the world.



North America	International
Université de Montreal, CA	University of Strathclyde, United Kingdom
University of Guelph, CA	Centre for Quantum Technologies, National University of Singapore
University of Waterloo, CA	ETH Zurich, Switzerland
Massachusetts Institute of Technology, USA	Kavli Institute of Nanoscience, TU Delft, Netherlands
	University of Birmingham, UK
	Tsinghua University, China

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

Since 2015, 16 IQC PhD alum have been awarded postdoctoral fellowships. These alum represent a group of early researchers dedicated to advancing their work in quantum information at IQC. In addition to attracting highly qualified young researchers, IQC postdoctoral fellowships are a proven method to seed further quantum research across Canada with former IQC postdocs holding faculty positions at Mount Allison University, Université de Sherbrooke, McGill University, University of Ottawa, Carleton University, Toronto Metropolitan University and University of Waterloo, to name a few examples.

Attracting Talent – Graduate Students

IQC welcomed 63 new graduate students this past year from 511 applications, bringing the total current number of master's and PhD students to 208 (88 and 120, respectively). The growth of the graduate program in 2021-2022 represents a return to normal growth for graduate students at IQC; the dip to 197 students in 2020-2021 (from 203 the previous year) was an aberration caused by uncertainty early in the Covid-19 pandemic. IQC accepts applications from some of the most recognized schools across Canada and around the world. The table below illustrates the range of institutions our applicants come from, including applicants from 8 of the 10 Canadian provinces.

Canada	International	United States
Concordia University	Delft University of Technology	Dartmouth College
University of Manitoba	Tsinghua University	Stanford University
University of Windsor	Federal University of Sao Carlos	Massachusetts Institute of Technology
Mount Allison University	Indian Institute of Technology Delhi	California Institute of Technology
University of British Columbia	University College London	Yale University
	École Normale Supérieure Paris-Saclay	



A full list of current graduate students currently studying at IQC can be found in Appendix F on page 87.

Graduate Student Awards

The best and brightest minds are studying and researching at IQC, earning awards and scholarships in recognition of their work. These awards not only provide students with the funding needed to devote themselves to their studies, but also demonstrate their research excellence. In the last year, 193 IQC students were collectively granted 560 separate awards.

Of the 193 IQC students that earned awards and scholarships, 45 were female (23%) and 12 additional awarded students did not report gender (6%). Overall, 93% of all IQC graduate students receive awards including 96% of female students and 100% of non-reporting students, demonstrating the ubiquitous excellence of IQC students. Additionally, when considering all graduates students, IQC has made strides towards achieving gender equity, increasing women and non-reporting students from 47 students in 2020-2021 to 59 in 2021-2022. This is a 5% increase towards gender parity and moves IQC forward in its goal of meeting the Innovation, Science and Economic Development Canada 50-30 Challenge.

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

- 9 Mike & Ophelia Lazaridis Fellowships
- 1 IQC Entrance Award
- 60 International Doctoral Student Awards
- 13 International Master's Awards of Excellence
- 1 IQC Achievement Award
- 1 Marie Curie Graduate Student Award
- 2 NSERC Alexander Graham Bell Canada Graduate Scholarships - Doctoral
- 7 NSERC Alexander Graham Bell Canada Graduate Scholarships - Master's
- 5 NSERC Postgraduate Scholarships - Doctoral
- 3 NSERC Vanier Canada Graduate Scholarships
- 19 President's Graduate Scholarships
- 1 Raymond Laflamme and Janice Gregson Graduate Scholarship for Women in Quantum Information Science
- 3 Ontario Graduate Scholarships
- 2 QEII-Graduate Scholarships in Science and Technology



Attracting Talent – Undergraduate Students

IQC offers many opportunities to expose undergraduate students to research. Students can apply primarily in tandem with applications to the annual Undergraduate School for Experimental Quantum Processing (USEQIP) for a chance to stay for a research term following the program, or they can apply for a research position outright.

Uncertainty surrounding travel, residency and building access due to Covid-19 resulted in USEQIP being offered online in May of 2021 and the Undergraduate Research program continued remotely. The worldwide pandemic, combined with varying travel and employment restrictions in Ontario and across the world forced changes to the ways that IQC engages with undergraduates. For example, the total number of undergraduate research assistants in 2021-2022 fell to 45 (from 57 the previous year) but the number of co-op students at IQC increased to 22 for the same period, 15 of whom were employed by faculty in research roles. The availability of a robust co-op program at Waterloo resulted in a smooth transition from one hiring program to another with no change in undergraduate engagement for IQC faculty members. IQC also continued to hire co-op students in scientific outreach, marketing, and web design roles, as it has for several years.

The impact of programs like USEQIP has inspired past participants to further their academic studies at their home institution, and then return to IQC for graduate school. Since the program's inception in (2009), dozens of past USEQIP participants have returned to IQC to pursue graduate studies. USEQIP participants often note that advanced degrees seem more accessible after participation in the program and are attracted to IQC in particular:

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

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

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

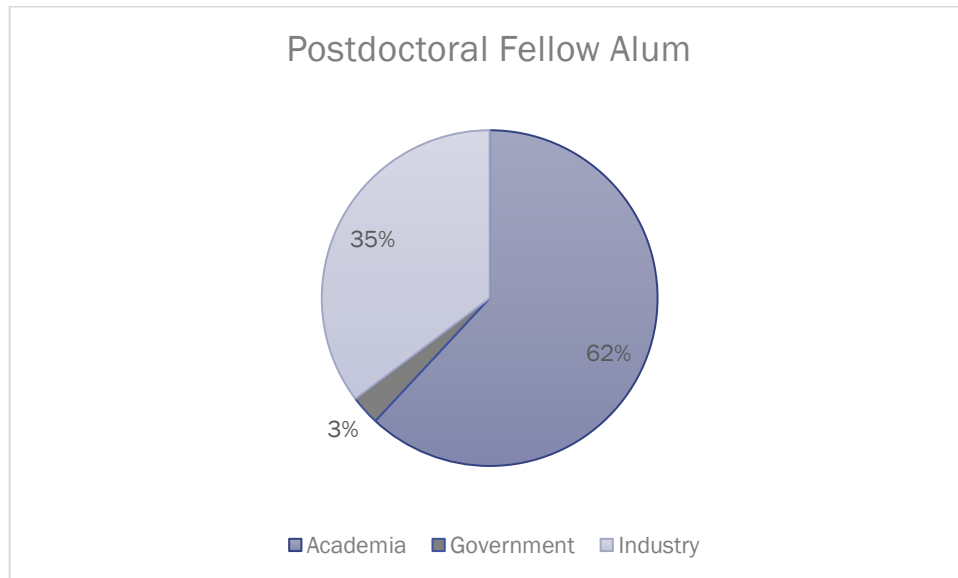
IQC Alum: Building the Quantum Workforce

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



Postdoctoral Fellows Alum Overview

After leaving academia, postdoctoral fellow alum are regarded as role models, visionaries, and leaders of the quantum industry by their peers. Our alum leave campus and become global citizens who impact academic, industry and government sectors. Below is a representation of where IQC postdoctoral fellows have gone as of March 31, 2022:



PostDoc Alum Profiles

Zhengfeng Ji – Postdoctoral Fellow 2011-2016

Zhengfeng Ji has made significant contributions to quantum complexity theory over the last decade. Now a professor at the Department of Computer Science and Technology, Tsinghua University, Ji's interest in this field started during his time as a postdoctoral fellow at IQC. Influenced by mentors Richard Cleve and John Watrous, Ji began working on nonlocal games, now an important topic in quantum complexity theory.

The focus of Ji's contributions has been on multi-prover interactive proofs (MIP*). Together with his collaborators, Ji has given a complete characterization of the complexity of MIP*, showing that it is as hard as the Halting problem. "The result is a surprise in quantum complexity theory and has deep connections to computer science, mathematics, and physics," said Ji.

Ji credits his postdoctoral fellowship at IQC as a critical period in his career. It helped develop his taste and persistence for research, which has contributed to his ongoing professional success. Now as a professor at Tsinghua, he remains connected to IQC as



an IQC affiliate and a research collaborator. Ji recently collaborated with both Debbie Leung and John Watrous, IQC faculty members, on separate papers.

Fang Song – Postdoctoral Fellow 2013-2016

Fang Song has constructed novel quantum cryptographic primitives, including work in zero-knowledge proof systems and pseudorandom quantum states, and designed efficient quantum algorithms, which offer guidance on the development of next-generation quantum-safe cryptosystems.

Song said that IQC “helped me form a broader view of the possible directions my research could entail.” The breadth of research in Quantum Information Processing (QIP) at IQC and first-hand data from experimentalists helped to refine the theoretical foundations of Song’s work and kept him connected to real-world problems.

Song’s PhD work at Penn State exposed him to high level research and led him to choose IQC for postdoctoral work where “top researchers from such diverse backgrounds get together and collaborate in an organic way.” Now, as a professor in the department of computer science at Portland State University Song’s work “investigates how quantum computing changes the landscape of cryptography and complexity theory in a rigorous way.”

Song’s research keeps him connected with current and former IQC members, connections which are evident in his 2020 paper on [‘Zero-Knowledge Proof Systems for QMA’](#) with co-authors Anne Broadbent (former IQC postdoctoral fellow and current affiliate), Zhengfeng Ji (former IQC postdoctoral fellow and current affiliate) and John Watrous (faculty member at IQC).

Jean-Francois Biasse – Postdoctoral Fellow 2014-2015

Jean-Francois Biasse is a professor of mathematics and director of the Center for Cryptographic Research at the University of South Florida, where his current research focuses on the upcoming transition to new public key cryptographic primitives.

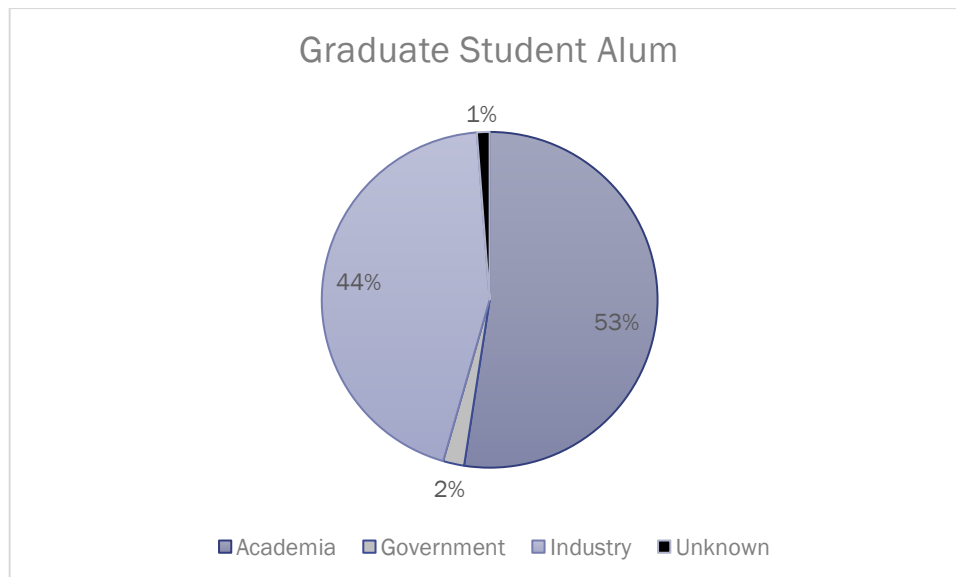
After a postdoctoral fellowship focused on cryptography, Biasse chose IQC because he wanted to “further interact with cryptography experts that were specializing in PQC (post-quantum cryptography).” Working with Dr. Mosca, Biasse was able to make significant contributions to the design of quantum algorithms shortly after starting at IQC.

The skills Biasse acquired at IQC are now used “developing quantum algorithms that pertain to the design and analysis of cryptosystems that resist attacks from quantum adversaries.” Biasse said, “IQC really had a defining role in my journey as an academic because it helped me acquire new quantum computing skills that are essential to my research agenda.”

Biasse continues to work with current and former IQC postdocs with a focus on cryptography, publishing papers as recently as 2020 with incoming IQC postdoc Dr. Xavier Bonnetain and former postdoc Dr. Fang Song in 2019.

Graduate Students Alum Overview

This year, IQC proudly granted degrees to 31 Master’s students and 14 PhD students, bringing the total number of student alum to 352 cumulatively. These researchers are employed in a diverse range of positions, from academia to industry and government, both within Ontario and around the world. As of March 31, 2022, 34 IQC graduates are working in the Quantum Information (QI) field in Canada, of which 6 are women. An additional 18 IQC graduates are employed as postdoctoral fellows at Canadian Universities. The chart below indicates the sectors where IQC graduate students have moved on to after leaving IQC, where known.



Student Alum Profiles

Phil Kaye (MMath Combinatorics & Optimization, PhD Computer Science)

Phil Kaye embodies the interdisciplinary nature of quantum research. Before earning his doctorate in Computer Science at IQC in 2007, Kaye completed his undergraduate degree in Systems Design Engineering, followed by a Master’s in Mathematics. He credits his education at IQC for giving him the scientific background and strong professional network to be able to bring an expert perspective to his career.

Through Kaye’s career, he has helped shape the policies that have allowed IQC and Canadian universities to remain at the forefront of quantum information processing.



Kaye published a textbook with Ray Laflamme and Michele Mosca, contributed to the founding of the Quantum Industry Canada consortium, and played an instrumental role in developing the National Quantum Strategy for Canada.

In his current role with the National Research Council, Kaye leads the Applied Quantum Computing Challenge program. It's the first Challenge program dedicated to applied quantum computing. The program supports applied quantum applications and software with grants and funding contributions.

“The impact of my work is in supporting the ecosystem through program development, stakeholder engagement, and supporting a range of Government of Canada quantum initiatives,” said Kaye. “My years at IQC also allowed me to build a strong network of professional relationships with leaders in Canada’s quantum community, and these connections are very important to my current work.”

Stacey Jeffery (MMath Combinatorics & Optimization, PhD Computer Science – Quantum Information)

Stacey Jeffery has published research on quantum homomorphic encryption, solved a fifteen-year-old open problem about quantum walk algorithms and founded a network for women in quantum computing in the Netherlands.


Her path through quantum research began at IQC. “I took an undergraduate course in quantum computing while studying computer science at the University of Waterloo, which led me to become an undergraduate research assistant at IQC, under Michele Mosca,” Jeffery said. “I guess I liked it so much I didn't leave until I had finished a PhD.”

Jeffery’s deep interest in quantum computing led her from Waterloo to Pasadena (Caltech), to her current work as a Senior Researcher at CWI (Centrum Wiskunde & Informatica) in Amsterdam where she continues to do theoretical research in quantum algorithms with an eye toward making tools that make it easier to design future quantum algorithms.

Jeffery acknowledges that the community at IQC played an important role in her success. “[IQC] had a fantastic community of other students from whom I learned a great deal,” she said. “There were always people visiting from other institutes, and as well as often workshops or conferences being hosted at IQC. This, as well as a generous travel allowance to go to conferences and visit other groups, helped me to grow a strong network by the time I finished my PhD, which has been crucial to my career.”

Srinivasan Arunachalam (MMath Combinatorics & Optimization – Quantum Information)

Srinivasan Arunachalam finished his master’s degree in Combinatorics & Optimization (Quantum Information) at IQC in 2014. Since then, Arunachalam completed his doctorate at the Centrum Wiskunde & Informatica in Amsterdam, finished a post-doc at the Center for Theoretical Physics at MIT and is currently at the IBM T.J. Watson Research Center where he focuses on researching and developing quantum algorithms.



Arunachalam said that “IQC was the top choice for studying quantum computing because of their internship and graduate program.” The quantum computing lectures and research Arunachalam did while at IQC has “played an important role in the [my current] research I do currently.” he said. Arunachalam also interned at IQC with Michele Mosca and Anne Broadbent for 3 months before he arrived in Waterloo.

His current work for the IBM T.J. Watson Research Center is focused on Quantum algorithms and learning theory. Arunachalam also continues to work with IQC postdocs, visiting Waterloo in 2019 and publishing with former IQC members in 2019 (Nathan Wiebe) and 2020 (Robin Kothari, Andrew Childs, Alexander Belovs & Anurag Anshu).

New Quantum Technology Program: Master of Science in Physics

The inaugural year of the Master of Science Degree in Physics with a specialization in Quantum Technology program is underway. This 12-month program offered by the Department of Physics and Astronomy with partnerships through IQC and TQT provides a rare opportunity for students to gain expertise in quantum information theory and experiments.

A unique component of the program includes access to the Quantum Explorations Space (QES), a dedicated space to support quantum training activities. The QES showcases quantum technologies in an interactive environment. Three specialized laboratory courses offered in the QES provide Quantum Technology MSc students with hands-on learning using state-of-the-art quantum devices:

- [Laboratory on Control of Quantum Technology](#)
- [Laboratory on Photonic Quantum Technology](#)
- [Laboratory on Low Temperature Quantum Technology and Nanofabrication](#)

Students develop skills and experience in the field through the laboratories while further enhancing their knowledge of the underlying theory and experimental work. Current students appreciate the integration of knowledge and practice through a realistic introduction to the field of quantum information.

In addition to the laboratory courses, students take core quantum information courses for a solid theoretical background while choosing electives from the world’s most comprehensive graduate program in quantum information. Students can also leverage the opportunity to network with a large collective of researchers, industries and start-ups at the forefront of quantum technology.

Students graduating from the program are well-positioned for careers in quantum industry or further graduate study.



Expanding Connections

IQC's graduate student recruitment efforts have continued to be successful through fiscal 2021-2022 with 511 unique applicants to IQC's graduate programs over the course of the year. IQC staff reached out to students at events like Prospective Medical Professionals (Pump+), the Canadian Conference for Undergraduate Women in Physics (CCUWiP), and graduate fairs run by Women in Science and Engineering (WISE), McGill University and the University of Waterloo. IQC staff have also sought to create a bridge between students and industry, participating in events like the Canadian Undergraduate Physics Conference (CUPC), Grad & Industry Fair and with presentations at Quantum Economic Development Consortium for the Technical Advisory Committees (QED-C TAC) on Outreach and Education.

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

- Five IQC faculty members participated in the Quantum Days Conference in February 2022, including Michael Reimer, Matteo Mariani, Michal Bajcsy, Na Young Kim and Raymond Laflamme contributing to the first 2 days of the 3-day conference.
- IQC Faculty members also contributed talks at various conferences such as QIP 2022, CAP Congress, QCrypt 2021 and the IEEE CEO Summit on Quantum Computing.

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


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

Workshops

Schrödinger's Class, November 30-December 5

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

In FY 2020-2021, Schrödinger's Class was delivered online and recorded a significant increase in participation. In FY 2019-2020 IQC was able to host 39 participants in-



person, in FY 2020-21, IQC hosted 130 people and found 112 teachers were highly engaged² with the curriculum, this represents an almost 300% increase in attendance – something that IQC could not accommodate in-person. This demand continued in FY 2021-2022 when IQC hosted 132 people with 109 highly engaged with the curriculum including international instructors from Virginia. This stable but high demand for access to engaging Quantum material is a demonstrates there is increased demand and we continue to evaluate new methods for supporting secondary school teachers and students moving forward.

Major Conferences

IQC remains committed to hosting conferences in Waterloo and are actively planning for conferences when they can be hosted safely for a wide variety of audiences. Restrictions in Ontario have been lifted subsequent to March 31, 2022, and remaining restrictions at the University of Waterloo have also been lifted as of May 2022. With these limits removed, IQC will begin hosting in person conferences in June of 2022.

Seminars & Colloquia

With frequent events, IQC's schedule of seminars and colloquia consistently keep the research community and their respective visitors engaged. This past year, IQC hosted 39 seminars, 14 of which were delivered by and for students, as well as and 3 colloquia. The student seminar series introduced in FY 2019-2020 continues to serve as a way to interconnect IQC members, allowing students to share results of their ongoing research, to be exposed to research outside of their immediate research area, and to serve as a platform to develop presentation skills. The total number of seminars increased slightly compared to 2020-2021 but remained lower than previous years due to Covid-19 related cancellations and postponements.

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

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



Sponsored Conferences & Workshops

Each year, IQC commits to supporting external conferences and workshops to encourage opportunity for collaboration among a global network of researchers. As travel restrictions eased in various jurisdictions throughout the year, IQC was able to more than double its sponsorship compared with 2020-2021. IQC sponsored 8 external partner events which are listed in the chart below, and remains committed to supporting relevant events as opportunity increases:

Date	Conference	Location
May	Pint of Science Canada Online Festival	Virtual
May	49 th Annual Canadian Operator Symposium (COSy)	Virtual
June	18 th International Conference on Quantum Physics and Logic (Gdansk & Online)	Poland & Virtual
November	Canadian Undergraduate Physics Conference (CUPC)	Virtual
November	McGill Physics Hackathon	Virtual
February	Quantum Days	Virtual
February	QHack 2022	Virtual
March	Conference on Quantum Information Processing (QIP)	California & Virtual



Objective C

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

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

Planned Activities:

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

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

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

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



Innovate UK-Canada project to benchmark and overcome noise and errors in near-term quantum hardware devices – IQC lead Raymond Laflamme

UK-based quantum software start-up [Phasecraft](#) began a new project facilitated by Innovate UK to reduce noise and errors on near-term quantum hardware.

Phasecraft was awarded the project grant from UK Research and Innovation (UKRI), the UK's innovation agency, and a team with internationally recognised academic and industry experts from the University of Waterloo's Institute for Quantum Computing (IQC) and Perimeter Institute for Theoretical Physics in Canada, and University College London in the UK. The institutes are three of the world-leading quantum computing research centres with strength in quantum error correction and fault-tolerant quantum computing. Canada-based start-up Quantum Benchmark (now Keysight Technologies) will contribute expertise and access to their industry-leading software system for error diagnostics and error suppression to improve and validate hardware performance for quantum computing applications.


The multi-phased project will:

1. Benchmark noise and diagnose dominant errors on quantum hardware platforms
2. Develop new error-resilient algorithms that can be implemented on NISQ (noisy, intermediate-scale, quantum) hardware where full fault-tolerance is beyond reach.
3. Integrate error diagnostics, error suppression and error mitigation with algorithm design: algorithms designed around accurate hardware error models with error mitigation and error suppression customized to industrially-relevant applications and algorithms.
4. Develop a feedback and refinement loop to refine error modelling, error mitigation, algorithm design and implementation on hardware.
5. Demonstrate and validate desired performance for use cases on near-term quantum hardware.

UK-Canada research partnership aims to expand global quantum network – IQC lead Thomas Jennewein

The quantum internet will allow quantum-secure communication on a global scale. A new collaborative project between the UK and Canada, that has been awarded funding from the [Quantum Communications Hub](#), will establish a key satellite link for quantum communication across the Atlantic.

Quantum key distribution (QKD) is a method for distributing encryption keys which is secure against eavesdropping or decryption. QKD is being rolled out worldwide across terrestrial, fibre-based networks. For intercontinental distances, QKD will have to rely on satellites, which exchange particles of light called photons with ground stations to generate the encryption keys.



The [Quantum Encryption and Science Satellite \(QEYSSat\)](#), led by the Canadian Space Agency and supported by researchers at the University of Waterloo, is currently on track to be launched into a low-earth orbit in early 2024. The new project, awarded by the Hub to researchers at Heriot-Watt University will allow connections from UK-based ground stations to QEYSSat using a new high-rate entangled photon source.

Further progress towards a global quantum secured communications network in space is being made through another on-going project that received funding bilaterally from the UK (via Innovate UK) and Canada (via Natural Sciences and Engineering Research Council of Canada) in November 2020, which will further expand the capabilities of the QEYSSat mission. The consortium project, '[ReFO](#)', which is jointly led by Quantum Communications Hub partners Craft Prospect (UK team) and the University of Waterloo (Canadian team together with Honeywell Canada, the Canadian Space Agency, and the University of Calgary), aims to integrate a source of quantum signals developed by Hub partners the University of Bristol and the University of Strathclyde with a novel protocol devised by the University of Waterloo team. This system will enable the QEYSSat microsatellite to transmit quantum signals using auto-compensation that will simplify the alignment between space and ground quantum states. The transmitter will connect with ground stations on both sides of the Atlantic, acting as a proof-of-concept demonstration for a global quantum secured communications network.

Be a catalyst for collaborations of quantum information scientists

IQC provides an atmosphere that encourages and celebrates collaborations at every level. Below are descriptions of collaborative projects that were either initiated or continued over the past year. Appendix D, on page 81 provides a full list of all collaborative efforts this year (note: this list does not include co-authored publications.)

CIFAR Quantum Information Science Program

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

NRC High-throughput and Secure Networks Challenge (HTSN)

National Research Council of Canada (NRC) is working proactively with talented Canadian partners and collaborators to tackle the code breakers of the future. Under the NRC's High-throughput and Secure Networks Challenge program, they are aiming to ensure that Canada's networks in both densely populated urban areas and rural and remote expanses are protected from quantum threats.

Kitchener, Ontario-based evolutionQ, a pioneer in quantum-safe cryptography, is led by IQC's world-renowned quantum computing experts Dr. Michele Mosca and Dr. Norbert Lütkenhaus. The company's experience in writing software for such security products and services makes them an ideal partner for industry and government as they pursue infallible methods for defending Canadian data from quantum threats.



Canada Foundation for Innovation (CFI)

Crystal Senko's research program was among the 21 projects at the University of Waterloo to receive an award from the Canadian Foundation for Innovation's (CFI) [John R. Evans Leaders Fund](#) (JELF).

A faculty member in the Department of Physics and Astronomy and IQC, Senko received over \$200,000 to continue her research in the Laboratory for Trapped Ion Quantum Computing with Nonidentical Qubits, which aims to develop new kinds of trapped ion quantum computers.

Funding provided through the JELF provides promising faculty members with research support, assists in recruiting and retaining outstanding researchers and helps researchers acquire tools to enable their work in areas that are innovative, high quality and that meet international standards.

Promote collaborations through participation in national and international conferences

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

- Single-photon source based on a quantum dot emitting at cesium wavelength, SPIE Photonics West
- Challenges for building a silicon-based quantum computer, ISQED Symposium
- Angstrom-scale nuclear magnetic resonance diffraction: a route to atomic resolution magnetic resonance imaging, American Physical Society
- Improved upper bounds on the stabilizer rank of magic states, Simons Institute for the Theory of Computing Reunion Workshops
- Programmable Quantum Simulations with Laser-cooled Trapped Ions, QuanTalk
- Ultracold Chemistry with triplet molecules, CAP Congress
- Novel directions for advancing satellite based quantum communication, International Symposium on Quantum Science
- What are the options for building a large scale quantum computer?, Institute of Theoretical Physics
- Capacity approaching codes for interactive quantum communication in the low noise regime, 5th Quantum Software Consortium General Assembly 2021
- Dimension Reduction in Quantum Key Distribution for Continuous- and Discrete-Variable Protocols, Qcrypt 2021

- Threats to and from Quantum Cryptography, Downstream Natural Gas Information Sharing and Analysis Center
- $SU(2)$ hadrons on a quantum computer, CERN “Theory Colloquium”
- The Glued-Trees Problem Revisited, Algebraic Graph Theory and Quantum Information at the Fields Institute
- Controlling light at the nanoscale with shaped nanostructures, Global Webinar on Laser, Optics and Photonics
- The membership problem for quantum correlations is undecidable, University of Innsbruck
- Giant c-axis Nonlinear Anomalous Hall Effect in T_d - $MoTe_2$, Materials Research Society Spring Meeting
- Applications of Quantum Computing for Data Science, Synthetic Intelligence Forum
- Giant Artificial Atoms and Programmable Topological Waveguides, Waveguide QED 2021
- Tight 2-designs in complex projective space, Open Problems in Algebraic Combinatorics
- From QM to QuIN, 2021 Quantum Week

Organize conferences with multidisciplinary participants

When planning major conferences, IQC remains committed to promoting the multidisciplinary basis of quantum information science. Due to pandemic restrictions IQC was unable to organize larger-scale conferences in FY 2020-21. These restrictions persisted provincially and locally through 2021-2022. However, IQC adapted quickly and hosted numerous virtual panels, roundtables and seminars which continued in 2021-2022. In FY 2022-2023, we are looking forward to hybrid conference models as well as a return to in-person gatherings as restrictions lift. We look forward to continuing our past successes with the Canadian Association of Physicists, Pint of Science and CAGIS, among others.

Long-term Academic & Scientific Visitors

IQC hosts leading academic visitors from organizations around the world. These colleagues and collaborators come for a number of reasons and stay for varied amounts time to conduct research, collaborate, share knowledge and present talks. In FY 2021-22, IQC researchers hosted 20 visitors from around the world. Visiting organizations included:

Domestic	International	United States
Université de Sherbrooke	Free University of Berlin, Germany	Harvard University
University of Toronto	Karlsruhe Institute of Technology, Germany	Texas A&M University
University of Ottawa	Institute for Quantum Optics and Quantum Information, Austria	University of Texas at Austin

Over the last year, IQC has built new and strengthened existing relationships with other Canadian universities and organizations in quantum research and technology. We leveraged technology to continue to offer our Visitor Program and bring leading international researchers to the Institute. In FY 2021-22, 90% of scientific visitors were from outside Canada (18/20).

A full list of academic and scientific visitors can be found in in Appendix H on page 96.

IQC online: Quantum Online Learning Library (QuOLL)

The Quantum Online Learning Library will create new learning opportunities in quantum via free online courses, lectures and instruction taught by IQC researchers. The primary audiences include lifelong learners, quantum enthusiasts, and educational institutions without in-house quantum expertise looking to expand/augment their programming. Making this course content available to lifelong learners and the general public supports IQC's objective to provide education and raise awareness of quantum, strengthening IQC's position as an authoritative source on quantum information science and technology. This library will be launched in 2022-2023, but production is well underway with the first series of videos scheduled to be launched for the fall 2022 term.

Objective D

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

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

Planned Activities:

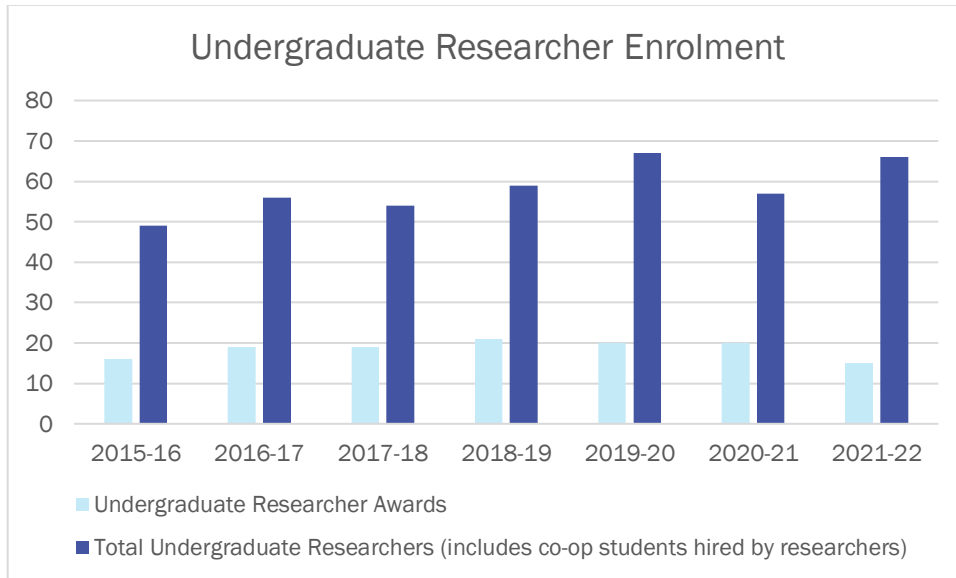
- Hosting USEQIP (undergraduate) and QSYS (high school) summer schools
- Hosting the annual high school teacher's workshop (Schrödinger's Class)
- Hosting outreach events including public lectures to increase the knowledge of event participants on quantum information and IQC
- Presenting dedicated STEM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

USEQIP

In 2021-2022 IQC hosted its annual Undergraduate School for Experimental Quantum Information Processing (USEQIP) virtually from May 31 to July 29 on Monday and Thursday evenings from 6-10 p.m. This program typically consists of lectures introducing quantum information theory and experimental approaches to quantum devices, followed by 30+ hours of hands-on exploration of Quantum Information Processing (QIP) using the experimental facilities at IQC. However, due to the virtual nature of this year's USEQIP, the hands-on exploration was replaced by live demonstrations, complete with experimental error and vivid interactions with IQC and industry demonstrators in real-time.



A virtual USEQIP confirmed that there is a significant demand at the undergraduate level for a high-level quantum information curriculum. By offering the program virtually, program enrollment jumped by almost 50% (28 in 2019-2020 to 41 in 2021-2022) and also saw the highest number of applications IQC has received. Additionally, even with uncertain employment rules in Ontario in 2021-2022, the number of undergraduates employed by IQC researchers increased to near highest levels.



QCSYS

IQC hosted its annual Quantum Cryptography School for Young Students (QCSYS [will be QSYS in the future]) summer school from August 3 to 13, 2021. With lessons from the first virtual program in 2020, QCSYS was refined for virtual delivery, and the final program included 18 lessons spread over 9 weekdays.

In August 2020, with a virtual format IQC was able to accommodate 110 highly engaged³ high school students from around the globe. In August 2021, the enrolment jumped again to 136 students for the second virtual delivery of the program. QCSYS’s jump in enrolment indicates an extraordinary interest in quantum topics for various audiences, such as young students and the general public, and it also highlights IQC’s reputation as a world-class institute for quantum information science research.

In a follow-up survey to students once the summer school had concluded, 96.8% of respondents rated their overall experience at QCSYS as excellent (70.4%) or good (26.4%). 100% of respondents said that they would actively encourage people to apply (66.7%) or if asked, they would encourage people to apply (33.3%). 89.6% of respondents strongly agreed with the statement, “QCSYS exposed me to ideas not available in my high school classes.”

“My experience in this program was really interesting, helpful, and fun. However, I'm a little sad that if QCSYS is in person next year, there won't

³ Attended more than 75% of all lectures.

be as many people in it as there was this year. I suggest that there should somehow be a way to include more people. Maybe, have the program run multiple times a year if possible.”

“I loved this program, and if there were any other quantum computing related programs offered, I would be first in line to attend! Thank you to all the lecturers for making this experience wonderful!!”

“Thank you for the amazing two weeks. This course as opened my eyes to many more opportunities and paths I could go down in the future.”

Schrödinger’s Class

IQC hosted its annual high school teacher workshop, Schrödinger’s Class, from November 30 – December 5.

Despite the pandemic, Schrödinger's Class was a resounding success in 2020. At that time, IQC had several months to pivot and was able to incorporate new equipment and lessons learned from a worldwide shift to online program delivery. Schrödinger's Class in 2021 was equally successful and sometimes engaged teachers for far longer than the scheduled 90 minutes with Q&A sessions following the workshops.

As in 2020, Schrödinger's Class was held as two separate virtual streams for 2021; as noted above (pg. 49), with attendance and engagement holding steady when compared to 2020, but with significantly more capacity and reach when compared to in-person delivery. Stream 1 was the weeknight stream that occurred during 3 evenings from November 30 – December 2. Stream 2 was the weekend stream that occurred on December 4 and 5. Both streams included 3 separate 90-minute sessions which included lectures provided by John Donohue and multiple breakout discussions. The 3 session topics were: Quantum Superposition & Light Polarization, Wave-Particle Duality and Interference, and The Uncertainty Principle.

In a survey of the teachers following the workshop, 92.8% of respondents replied that they would “actively refer colleagues to the program” (75.9%) or “refer if asked about the program” (16.9%). When asked “How many teachers would you share Schrödinger's Class material with?” on average each participant answered that they would share this material with an additional 12 teachers.

“The class was designed with foresight. I felt that I was provided with necessary information to progress through levels of understanding (or future understanding). I did not find that I was aware of the learning objective at each session (i.e. we will now demonstrate the lesson as you would use it in the classroom).”

“I like the material that was made available, including the slides and the youtube video. It was all very well prepared. I also liked the question

break. If possible, four sessions of 1h30min each would help, but this is a minor point.”

“Thank you for providing supplies for us to work with. Also, thank you for the resources to continue our learning!”

Public Lectures

This year, IQC closed the ‘Fireside Chat’ series on YouTube, and began a series titled ‘Quantum Today’ that addressed the overall need for more scientific content. Interestingly, Alan Jamison book-ended the year appearing in the final ‘Fireside Chat’ and the final ‘Quantum Today’ episode (of the fiscal year). In his ‘Fireside Chat,’ Jamison discussed his personal journey towards cutting-edge physics. In ‘Quantum Today’ he discussed his recently published paper in Science, worked on in collaboration with the Ketterle lab at MIT, that focuses on new ways to control chemical reactions with quantum interference.

‘Quantum Today’ also featured the work of 5 additional research groups at IQC and included:

- Chung-You Shih and Kazi Rajibul Islam giving a talk called ‘New algorithm uses a hologram to control trapped ions’
- Luca Dellantonio discussing ‘A measurement-based variational quantum eigensolver’
- Twesh Upadhyaya discussing ‘Dimension Reductions in Quantum Key Distribution’
- Chris Wilson discussing ‘Simulating Quantum Particles on a Lattice’
- Andrew Cameron and Connor Kapahi discussing ‘Unlocking high-dimensional optics’

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

- Tomas Jochym-O-Connor (currently at IBM Research)
- Corey Rae McRae (currently the director of the Boulder Cryogenic Quantum Testbed, University of Colorado-Boulder)
- Juan Miguel Arrazola (currently at Xanadu)

IQC also collaborated with the Kitchener Public Library to provide the expertise (John Donohue) to moderate books talks for the new releases:

- ‘Where did the Universe come from?’ by Chris Ferrie and Geraint F. Lewis and

- ‘A Brief History of Timekeeping’ by Chad Orzel

High School Visits

IQC has continued to offer virtual class visits to high school physics classrooms across Canada. In these visits, quantum experts join a class virtually and share a presentation about quantum science and quantum information, taking questions from students about the field and pathways into research careers. The demand for virtual class visits exploded to over 5000 students this year across Ontario, Quebec, Alberta, and Manitoba, as well as into the US. Additionally, almost 400 elementary and middle school students, mostly in the Waterloo Region, were reached via presentations developed through various partnerships, including with THEMUSEUM and the Canadian Association for Girls in Science (CAGIS).


Promoting Science for Women & Girls

In addition to the work with CAGIS mentioned above, IQC had an additional 11 events that focused on promoting gender equity in STEM fields spanning every pre-graduate level of education in Canada. IQC had representation at PhysiX: Girls Matter Workshops aimed at elementary school children, CAGIS workshops supporting middle school aged girls, InspireHER Workshops promoting quantum to high school aged girls and a number of recruiting events for undergraduate-aged women. All these events underline IQC’s commitment to not only increasing gender equity at IQC but also to fostering a more inclusive environment where enthusiasm for ideas is spread widely and indiscriminately across Canada.

In November, IQC also held a virtual panel discussion titled ‘How I Got Into Quantum: A Graduate Student Perspective,’ featuring all female panellists. The panel showcased various paths that these women had taken to arrive at IQC, and included a discussion of their current and future interests. For this event live and on-demand viewers totaled 1000+ with more than 75 hours of watch time. The panellists featured were:

- Cindy Yang, PhD student at IQC in Electrical & Computer Engineering (inaugural winner of the Laflamme and Gregson Graduate Scholarship for Women in Quantum Information Science)
- Natalie Parham, Master’s student in Combinatorics & Optimization
- Joanna Krynski, Master’s student in Physics & Astronomy

As part of IQC’s commitment to equity and diversity, we strive to open doors for girls and women before they can apply to graduate school so that STEM-related graduate school is a viable opportunity. To drive gender parity, QCSYS (high school students) had 41% female identifying attendees, while Schrödinger’s Class (high school teachers) had 52% female identifying attendees. By helping girls and young women to see themselves in quantum information science, IQC strives to create a much larger talent pipeline for IQC and STEM programs in the future.



As important as it is to make space in graduate programs for girls and women, it's equally important to highlight examples of successful women in Quantum Science. To support that effort in November 2021, IQC, in partnership with the W Store, hosted a conversation between Dr. Chandra Prescod-Weinstein and IQC Communications and Strategic Initiatives Director Kayleigh Platz centred around Prescod-Weinstein's new book focusing on the Standard Model of Particle Physics. IQC also presented a talk titled 'A Framework for promoting Excellence in Science through Inclusion, Diversity and Accessibility' by Dr. Shohini Ghose, an IQC affiliate member, co-editor in chief of the Canadian Journal of Physics and director of the Laurier Centre for Women in Science. Both women demonstrate the possibilities for women in advanced physics.

Strategic Outreach Partnerships

IQC has partnered with organizations including the Kitchener Public Library and THEMUSEUM to bring quantum ideas and associations into virtual public spaces. IQC also has existing relationships with TelusSpark and Canadian Association for Girls in Science (CAGIS), and remains committed to engaging with corporate and non-profit partners to promote quantum science everywhere. We are focused on building new partnerships in FY 2022-2023, some of which have already begun to flourish.

Communications

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

New Stories and Earned Media

With research results reported on each year, IQC strives to promote its community's work to the mainstream media. This year, approximately 1,260 media mentions of IQC were recorded, translating to a potential reach of 1.7 billion impressions (the number of times that a post has been viewed on a feed). Media mentions increased significantly in FY 2021-22 returning to pre-pandemic levels, in part due to wire service reporting. Potential reach remains consistent with previous reporting periods.

Media outlets include (but are not limited to): Forbes, Yahoo! Finance, NPR's All Things Considered, Tech Radar, Popular Science, Physics Today, and Security Magazine. All mentioned or cited IQC or IQC researchers in the last year, demonstrating IQC's global presence in this emerging and international quantum industry.

Website

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



Traffic to the IQC website remained consistent with the previous reporting period. Overall traffic to IQC’s website increased compared to the previous year – there were 124,042 unique visitors in FY 2021-2022 compared to 108,510 in FY 2020-2021. Additionally, pageviews increased to 435,011 in FY 2021-2022, up from 320,553 in FY 2020-2021.

Approximately 72% of web traffic in the reporting period is from outside Canada, with visitors from the United States, India and China representing the largest proportion of new international visitors. Organic search was responsible for 53% of the traffic to the IQC website during the reporting period, meaning that the majority of IQC’s visitors found the website by using search engines.

The query “quantum computing” remains the biggest driver of traffic to the website, indicating that IQC is an important and authoritative search result for those looking to learn more about this quantum application.

IQC developed a new section called ‘Quantum 101’ that launched in August 2021. ‘Quantum 101’ is an engaging, accessible, and informative web experience. Since launch, ‘Quantum 101’ has attracted 89,052 new users and 330,508 pageviews.

Social Media

IQC continued to post informative and engaging content on social media for its followers throughout April 1, 2021 to March 31, 2022. More than 900 pieces of content posted across Facebook, Twitter, Instagram and LinkedIn generated nearly 977,000 impressions and more than 24,000 engagements. During the same period, the IQC YouTube channel garnered over 199,000 views and over 21,500 hours of watch time. IQC drew particular attention to IQC researchers’ accomplishments and impact with a comprehensive social media campaign for the 2021 Impact Report.

Throughout last year, IQC account growth across all social media platforms continued. Below are some highlights of social platform growth from April 1, 2021 to March 31, 2022. Consistent online growth is a positive sign that points toward IQC’s established position of being an authoritative voice in its field.

	New Followers	Total Current Followers	Increase
YouTube	3,116	24,600	14.9%
Facebook	112	5,541	2.0%
Twitter	1,202	16,464	7.6%
Instagram	324	1,513	27.2%



IQC continues to plan and implement new strategies to generate high quality, quantum-related content that is valuable for IQC’s social media audiences. In late 2021, IQC began implementing new tactics to improve social media performance and engage audiences with a focus on audience engagement, growth, and retention.

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

Impact Report


The [2021 Quantum Impact Report](#) went live in December 2021. For the first time, the Impact Report was published as a digital-first immersive online experience to showcase IQC and quantum research through concise storytelling, video and photography. The report was launched by direct email and supported by a comprehensive social media campaign. With above average open (45.7%, +9.4% avg) and click through rates (6.6%, +1.6% avg), the performance of the direct email campaign succeeded in reaching our audiences. So far, the social media campaign has made 70,451 impressions. There has also been a high engagement rate on social media, which has been entirely organic across all platforms. Engagement rate (ER) is defined as: Average Engagements/Average Impressions, where an ER of 1-3% is considered good and anything over 5% is high. Metrics below reflect December 14, 2021 through March 31, 2022.

Metric	Twitter	Facebook	Instagram
Eng. Rate (ER)	2.7%	3.8%	8.9%
Avg. ER	5.1%		

Video Engagement (YouTube)
Views: 1145
Watch time: 18.3 hrs
Avg. % viewed: 56.1%

Website traffic and time-on-page goal conversions have been used to measure content consumption. In Google Analytics, goal conversions have been set up and tracked. In only six weeks, the publication has 5,856 pageviews in 1,723 sessions. A bounce rate of only 23.9% demonstrates that readers are coming to the site and interacting with content. The overall goal conversion rate is 178%, demonstrating that readers are interested in and consuming the report content.

Goal conversions as %/overall web traffic			
1+ pages/session:	12.3%	30-second time on page:	11.6%
3+ pages/session:	6.5%	60-second time on page:	9.3%
5+ pages/session:	5.0%	90-second time on page:	7.6%



The digital publication was complemented with a short, high-level printed piece mailed to 266 recipients. There was a 21% engagement rate on the call to action to visit the online publication. By visiting the online publication, this call to action implored visitors to read the full report, engage with IQC and join the quantum journey. Printed copies of the highlight piece are also on campus and available to IQC members for stakeholder relations and distribution. The 2021 Quantum Impact Report is an engaging report that effectively bridges the awareness gap between quantum research and its potential impact.



Objective E

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

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

Planned Activities:

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

Supporting Quantum Industry and Ecosystem Connections

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

As of March 2022, IQC researchers collectively held over 40 patents, 30 licenses and 2 provisional patents granted in 2021-2022. Currently, IQC faculty have over 45 active patent applications pending approval.

IQC's research and innovative new technologies are influencing the development of new companies and creating a significant marketplace impact. To date, the below 16 currently active start-ups have emerged from IQC research.



IQC quantum spin-off companies:

- EvolutionQ
- Neutron Optics
- QuantumLaf Inc.
- Universal Quantum Devices
- SoftwareQ Inc
- SpinQ
- Aquabits
- Northern Quantum Lights
- High Q Technologies LP
- BioGraph Sense Inc.
- Qubic Inc.
- Single Quantum Systems
- QEYnet
- Foqus
- Q-Block Computing Inc.
- Aegis Quantum

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

While 40%+ of IQC principal investigators have commercialized their expertise and research through spin-off companies and patents, more are supporting the development of a quantum industry in other ways. These additional contributions include advising quantum companies (both quantum and non-quantum firms), coaching early alum focused on careers in industry and collaborating with accelerator and business development hubs in and beyond the Quantum Valley.

Transforming quantum ideas into impactful technologies

At IQC, research excellence and innovation go together. Its rich entrepreneurial culture attracts and supports quantum experts that choose to go beyond aspiration to develop impactful technologies. This success is exemplified by Quantum Benchmark, which developed commercial tools for characterizing and validating quantum processors. Quantum Benchmark was acquired in FY 2021-2022 by Keysight Technologies but continues to operate in the Quantum Valley around Waterloo. Further, this unique environment, combined with programs like the Quantum Alliance Program has led to several technological applications. Highlights include:

- Commercializing a quantum microwave system based on superconducting circuits producing maximum correlations with minimal added noise (Chris Wilson, Qubic).
- Developing novel graphene-based materials for bio-sensing and backplane electronics applications (Michal Bajcsy, BioGraph Sense Inc.)

- Developing Quantum Information algorithms and Machine learning techniques to enhance the sensitivity of Magnetic Resonance technology (Sadegh Raeisi, Foqus).

Promoting Entrepreneurial Ecosystems Opportunities

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

- In May 2021, IQC partnered with Creative Destruction Lab to highlight its Quantum program stream aimed at helping early-stage quantum start-ups grow and develop a pitch-ready prototype. The seminar was in partnership with TQT and Perimeter Institute and allowed the respective institutes and programs to highlight to the audience of students, researchers and primary investigators the different ways aspiring entrepreneurs can find support in the Quantum Valley.
- In May of 2021 Quantum Benchmark, founded by IQC faculty members Joseph Emerson and Joel Wallman, was acquired by Keysight Technologies. Keysight is an electronic measurement company with an estimated revenue range of between \$1 and \$10B and more than 10,000 employees worldwide. This acquisition demonstrates the value of knowledge being developed at IQC. Further, the intellectual property being developed remains in Waterloo and it is very much tied to the wider development environment in the Quantum Valley.
- In June 2022 it was announced that evolutionQ (founded by Michele Mosca and Norbert Lütkenhaus) raised \$7 million CAD in Series A financing, led by Quantonation. Much of this work for this financing took place during fiscal 2021-2022. The cryptographic and quantum secure solutions offered by evolutionQ are targeted toward financial institutions that have a high degree of cybersecurity and are very aware of the changing security landscape associated with quantum computing and technologies.

APPENDICES

A. Risk Assessment & Mitigation

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

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
Decrease in faculty negatively affects research output and reputation	High	Medium	8	If Canadian lockdowns and international travel restrictions remains long-term while other countries open up and resume normal operations, it may impede our ability to participate in in-person collaboration and research. IQC has a significant research output which contributes to ongoing reputational excellence. Decreasing faculty may negatively affect research output and consequently reputational excellence.	Continue to identify and implement new approaches to virtual collaborations. More aggressive recruiting in the face of increasing national and international competition for high performance individuals.
Transformational Technologies may render current research less relevant	High	Low	6	If IQC research is rendered less relevant, highly qualified personnel (HQP) and investment will go elsewhere.	Ensure a wide breadth of research to investigate in order to differentiate IQC from its competitors. Ongoing collaboration with partners to ensure research aligns with societal priorities and economic drivers . Continue applications for research funds to support and advance leading-edge applications, equipment, and breakthroughs.



IQC may be unable to recruit enough international HQPs	High	Low	6	Covid-19 travel restrictions prevent HQPs from entering, studying and working in Canada.	Diversify markets/countries from which students are recruited. Promote IQC sufficiently. Ensure excellent research.
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B. Publications

April 1, 2021-March 31, 2022

1. Bindel, N; Schanck, JM. (2021) Decryption Failure Is More Likely After Success. Post-Quantum Cryptography, PQCrypto 2020
2. Sinha, U. (2021) THE TRIPLE-SLIT EXPERIMENT. Scientific American
3. Anshu, A; Arunachalam, S; Kuwahara, T; Soleimanifar, M. (2021) Sample-efficient learning of quantum many-body systems. 2020 IEEE 61st Annual Symposium On Foundations Of Computer Science (FOCS 2020)
4. Scott, A; Jennewein, T; D'Souza, I; Hudson, D; Podmore, H; Soh, W. (2021) The QEYSSat mission: On-orbit demonstration of secure optical communications network technologies. Environmental Effects On Light Propagation And Adaptive Systems III
5. Di Matteo, O; Gamble, J; Granade, C; Rudinger, K; Wiebe, N. (2021) Operational, gauge-free quantum tomography. Quantum
6. Kuroiwa, K; Yamasaki, H. (2021) General Quantum Resource Theories: Distillation, Formation and Consistent Resource Measures. Quantum
7. Barnum, H; Graydon, MA; Wilce, A. (2021) Composites and Categories of Euclidean Jordan Algebras. Quantum
8. Wiersema, R; Zhou, CL; de Sereville, Y; Carrasquilla, JF; Kim, YB; Yuen, H. (2021) Exploring Entanglement and Optimization within the Hamiltonian Variational Ansatz. PRX Quantum
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Shayan Majidy	Fangzhou Yin
Sonell Malik	Yuming Zhao
Anastasiia Mashko	Shazhou (Joey) Zhong
Kieran Mastel	Jennifer Zhu
Ejaaz Merali	Artem Zhutov
Zachary Merino	Nicholas Zutt

Master's Students

Abhishek Anand	Angus Lowe
Amit Anand	Anton (Tony) Lutsenko
Satchel Jeanne Armena	Mary Katherine MacPherson
Joan Etude Arrow	Victor Marton
Mohammad Ayyash	Darian McLaren
Ali Binai-Motlagh	Rahul Menon
Jack (John) Burniston	Mayar Tharwat Mohamed
Nicole Caswell	Kimia Mohammadi
Albie Chan	Arsalan Motamedi



Sandra Cheng	Manar Naeem
Margie (Margaret) Christ	Olivier Nahman-Levesque
Anthony Chytros	Nicholas Olsen
Brady Cunard	Alev Orfi
Alex Currie	Parth Padia
Yvette De Sereville	Natalie Parham
Jack DeGooyer	Matteo Pennacchietti
Cary (Carolyn) Earnest	Matthew Piatt
Mohamed El Mandouh	Vinodh Raj Rajagopal Muthu
Collin Epstein	Shaun (Shixin) Ren
Xiaoxuan Fan	Marcel Robitaille
Taylor Fraser	Supratik Sarkar
Turner Garrow	Pravek Sharma
Ajith George	Kosar Shirinzadeh Dastgiri
Michael Grabowecky	Namanish Singh
Aaron Gross	Joshua Skanes-Norman
Lucas Hak	Zewen Sun
Zachary Hinkle	Hawking (XingHe) Tan
Anya Houk	Jacob Taylor
Omar Hussein	Devashish Jayant Tupkary
Noah Janzen	Twesh Upadhyaya
Dave Jepson	Anthony Vogliano
Scott Johnstun	Luyao Wang
Alexander Kerzner	Lemieux Wang
Bohdan Khromets	Maeve Wentland
Alexandra Kirillova	Evan White
Danny (Xiangzhou) Kong	Adam Winick
Michal Kononenko	Olivia Woodman
Joanna Krynski	Austin Woolverton
Sema (Fehime) Kuru	Wilson Wu
Tony (Anthony) Lau	Wenxue Zhang
Xiaoran (Nicole) Li	Zhaoxin Zhang
Sarah (Meng) Li	Xingyu Zhou
Junqiao Lin	Cheng Zhu
Guofei (Phillip) Long	Jingwen (Monica) Zhu



G. Invited Talks & Conference Participation

Faculty Member	Title/Subject	Institution/Conference
Michal Bajcsy	Single-photon source based on a quantum dot emitting at cesium wavelength	SPIE Photonics West On Demand: 01-02-22
	Manipulating single photons with atomic ensembles: tackling old challenges using nanophotonics	Quantum Days 2022: 08-02-22
	Nanophotonic platforms for quantum optics with atomic ensembles	CAP Congress: 01-06-22
Jon Baugh	Challenges for building a silicon-based quantum computer	ISQED Symposium: 08-04-21
	Single-electron devices: applications to quantum information	CQIQC seminar, University of Toronto: 04-06-21
	Single-electron devices: applications to quantum information	Raman Research Institute (India) seminar: 23-02-22
Raffi Budakian	Angstrom-scale nuclear magnetic resonance diffraction: a route to atomic resolution magnetic resonance imaging	American Physical Society in Chicago, USA : 01-03-22
	Angstrom-scale nuclear magnetic resonance diffraction: a route to atomic resolution magnetic resonance imaging	7th International NanoMRI Conference in Barcelona, Spain : 01-03-22
David Gosset	Fast simulation of planar Clifford circuits	CFCS Quantum Day, Peking University (online): 12-05-21
	Improved upper bounds on the stabilizer rank of magic states	Simons Institute Quantum Wave in Computing Reunion Workshop, Simons Institute for the Theory of Computing, UC Berkeley: 16-07-21
	Quantum walks, scattering theory, and universal computation	Fields institute workshop on algebraic graph theory and quantum information (online): 23-08-21
	Shallow circuits and the quantum-classical boundary	Perimeter Institute Colloquium (online): 22-09-21
	Classical algorithms for Forrelation	QIP 2022, Pasadena, USA: 07-03-22
	An area law for 2D frustration-free spin systems	QIP 2022, Pasadena, USA: 08-03-22
	How to simulate measurement without computing marginals	CMT/PyQuil Seminar, Perimeter Institute (online): 18-03-22
Rajibul Islam	Programmable Quantum Simulations with Laser-cooled Trapped Ions	Physics Colloquium, Colorado State University: 05-04-21
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	Physics Colloquium, Ohio State University: 06-04-21
	Trapped ion quantum simulation: opportunities and challenges	Discussion Meeting on Physics with Trapped Atoms, Molecules and Ions, ICTS, Bengalura: 21-05-21



	Programmable Quantum Simulations with Laser-cooled Trapped Ions	USEQIP 2021, Institute for Quantum Computing: 12-07-21
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	QIQT 2021, IISER Kolkata: 14-07-21
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	QuanTalk, IIT Madras: 11-11-21
	Programmable Quantum Simulations with Laser-cooled Trapped Ions	IACS, Kolkata: 21-12-21
Alan Jamison	Ultracold Chemistry with triplet molecules	CAP Congress: 07-06-21
	Ultracold Quantum	IQC: 14-12-21
	Quantum Today: Controlling chemical reactions with quantum interference	IQC: 24-03-22
Thomas Jennewein	QEYSSat 2.0: A Roadmap for Canadian Quantum Satellite Missions	Qeyssat 2.0 workshop: 15-02-21
	Novel directions for advancing satellite based quantum communication	International Symposium on Quantum Science, Technology and Innovation, RIKEN: 07-12-21
	The quantum internet and why satellites will be needed	WEH-Seminar on "Photonic Quantum Technologies": 17-03-22
	Quantum communication devices	CryptoWorks21 training program, QKD/UW: June 22-23rd 2021
	Quantum Key Distribution QKD	Emerging Technologies Workshop, DND: October 26 2021
	Novel avenues for robust free-space quantum communications	Thailand Quantum Technology Symposium: September 16 2021
Na Young Kim	Two-Flavor Bloch Exciton-Polaritons	Polariton Chemistry Webinars, April 20 th , 2021
	Solid-State Quantum Platforms: Bloch Exciton-Polaritons and Rydberg Excitons	UW Electrical and Computer Engineering Seminar Series, June 10, 2021
	From QM to QuIN	2021 Quantum Week, South Korea: June 27, 2021
	Where a photon meets an exciton: Bloch Exciton-Polaritons and Rydberg Excitons	The 51 st Winter Colloquium on the Physics of Quantum Electronics, USA: January 10, 2022
	Semiconductor Quantum Cavity QED Platforms	Quantum Days 2022, Canada: February 8, 2022
Raymond Laflamme	On Stephen Hawking	ISSYP at Perimeter Institute, Waterloo, ON: 21-07-21
	What are the options for building a large scale quantum computer?	Institute of Theoretical Physics, Paris-Saclay: 29-11-21
Debbie Leung	The embezzlement of entanglement and its applications	Quantum Software and Optimisation online workshop, Wallenberg Centre for Quantum Technology, Chalmers University of Technology in Gothenburg, Sweden: April 08-09, 2021
	Capacity approaching codes for interactive quantum communication in the low noise regime	5th Quantum Software Consortium General Assembly 2021, Track Quantum Networks Conference, Amsterdam, Netherlands: June 3-4, 2021



	Additive quantities cannot be more than asymptotically continuous	Division of Theoretical Physics, Quantum Information Theory Session, Virtual Canadian Association of Physicists Congress 2021: June 6-11, 2021
	The platypus of the quantum channel zoo	Oberwolfach workshop 2140b - Geometry and Optimization in Quantum Information, Oberwolfach Research Institute for Mathematics, Germany: Oct 3-9, 2021
	Quantum channel capacities	1st International Symposium on Trans-Scale Quantum Science (TSQS2021), University of Tokyo, Japan: October 25-29, 2021
Adrian Lupascu	Quantum Optics seminar	University of Waterloo: 02-12-21
	Synthetic Intelligence Forum	Virtual: 11-03-22
Norbert Lütkenhaus	Making Canada safe against known quantum-enabled attacks and driving economic prosperity through being a world leader in preparing digital systems to be quantum-safe.	Quantum Days: Apr 10-21
	QKD as performance metric for Quantum networks	Next Generation Quantum Networking Workshop 2021 : Apr 30-21
	QKD Networks and Application	DRDC Quantum Networking/Communication Seminar: Apr 7-21
	Quantum Key Distribution and its Security Claim	Arizona QKD-PQC Symposium: Apr 9-21
	Dimension Reduction in Quantum Key Distribution for Continuous- and Discrete-Variable Protocols	Qcrypt 2021: Aug 23-27-2021
	NICT Workshop	NICT Workshop: Dec 7-9, 21
	Quantum Key Distribution - useful or just fun?	Munich Quantum Stammtisch: May 12-21
	QKD networks and applications	EOCO2021 workshop on QKD: Sept 13-21
	Numerical Security Analysis for Quantum Key Distribution and Application to Optical Protocols	SAMOP 2021(DFG) Workshop: Sept 23-21
	QKD networks and applications	BSI Current Topics in QKD Workshop: Sept 9-21
Matteo Mariani	Superconducting Circuits: Quantum Probes for Dielectric Materials	Quantum Days 2022: 09-02-22
Michele Mosca	Toward a more resilient quantum-safe future	The 1st Yanqui Lake International PQC Standardization and Application Workshop & the 5th Asia PQC Forum: 24-04-21
	Cyber resilience in the quantum era	Organization of Canada Nuclear Industries "Cyber Security Week" online conference: 26-04-21
	National quantum development group	IQT New York Conference: 17-05-21
	Markets and Product Evolution for Post-Quantum Cryptography	IQT New York Conference: 17-05-21
	Perspective on Canada/EU collaboration	CAN-EU (virtual) Workshop (NSERC and European Commission), InCoQFlag, France: 30-05-21
	Can we afford to wait or should we be actively looking for solutions to protect the integrity of the existing cryptosystems?	OIST Quantum/Cyber Security Initiative – The Science, the Opportunities, and real-world Challenges, OIST/Keidanren virtual event: 01-06-21



	Cryptography in a quantum computing world: will our data be safe?	The Payment Canada Summit 2021: 04-06-21
	Technology Facilitating Access to International Markets	Horasis Extraordinary Meeting on the USA: rebuilding trust: 08-06-21
	Introduction to the quantum threat and quantum readiness	Organization of Canadian Nuclear Industries: 29-06-21
	Post quantum track	International Cryptographic Module Conference 2021 (virtual ICMC21), MD, USA: 02-09-21
	Quantum track	International Cryptographic Module Conference 2021 (virtual ICMC21), MD, USA: 02-09-21
	Threats to and from Quantum Cryptography	Downstream Natural Gas Information Sharing and Analysis Center: 15-09-21
	Preparing for the Quantum Threat	Quantum-Safe Canada Nuclear Industry Readiness, Canadian Gas Association group: 22-09-21
	Thailand Quantum Technology Symposium	Quantum Technology Research Initiative - Online: 26-09-21
	Talk on Post Quantum Computing	Aeronautical Telecommunication Network, IPS group at ICAO: 14-10-21
	Cybersecurity R&D Future and Gaps	SERENE-RISC final workshop: 20-10-21
	Update on the quantum threat timeline	Quantum security community meeting, World Economic Forum: 21-10-21
	Taking the Quantum Leap: How Quantum technology is set to transform long-distanced communications	Capacity Europe 2021: 21-10-21
	Preparing for Post-Quantum Cryptography	Energy & Utilities Sector Network (EUSN) Conference Call: 22-10-21
	Quantum Key Distribution	2021 Emerging and Disruptive Technologies (EDT) workshop, The Department of National Defence (DND): 26-10-21
	Why is quantum and why should I care?	Mitsubishi UW Quantum Readiness Symposia: 28-10-21
	National Quantum Development Groups	Inside Quantum Technology, New York, USA: 01-11-21
	Market and Product Evolution for Post Quantum Encryption	Inside Quantum Technology, New York, USA: 01-11-21
	Overview Talk	Canada-Germany Quantum Computing: Berlin Science Week Event: 02-11-21
	The Quantum Threat: Where Are We Today?	SecTor2021, Toronto, ON: 03-11-21
	Cybersecurity & Quantum: what steps City firms need to take	London, UK - Virtual: 10-11-21
	Are you ready for success in the quantum era	IEEE CEO Summit on Quantum Computing: 01-12-21
	All-Star Plenary Panel session on technology's impact and window into the future	The Great Canadian Data Centre Symposium (GCDCS21): Digital Innovation in the Next Normal, Hamilton, On: 02-12-21
	Bringing QKD to real world digital infrastructures	Quantum Innovation 2021, RIKEN, Japan: 08-12-21
	Post-Quantum Cryptography	The Third IEEE International Conference on Trust, Privacy and Security in Intelligent Systems, and Applications: 13-12-21
	Getting Ready for Quantum Computing: Cyber Risk Considerations	Global Risk Institute, Public Webinar: 31-01-22



	Quantum Computing and National Security	National Defense University's College of Information and Cyberspace (CIC) Quantum Lesson, Washington DC: 14-02-22
	NRC & DRDC sponsored workshop on future of Quantum Internet in Canada	hosted by The Quantum EncrYption and Science Satellite (QEYSSat), Waterloo, ON: 15-02-22
	Fireside chat on National Cybersecurity Strategy and Action Plan	Federal Executive Briefing with Sami Khoury, Canadian Centre for Cyber Security, hosted by Technation, ON: 24-02-22
	Are we ready for the quantum era? CPI	Waterloo, ON: 28-02-22
	National Quantum Strategy Standard Workshop	Standard Council of Canada and Innovation, Science and Economic Development Canada: 03-03-22
	Cross border cooperation in the research and development of quantum technologies	Canada and the United States in the New Quantum Tech Era, Joint US-Canada Quantum Event, the Wilson Center and the Embassy of Canada, Washington D.C: 09-03-22
	Intro to the quantum threat and quantum readiness	CANDU Owners Group Cybersecurity Peer Group: 21-07-21
	Quantum Computing view from Industry	IEEE Quantum Week Oct 18-22 Quantum Computing Workshop: 18-10-21
Christine Muschik	SU(2) Hadrons on a quantum computer	Annual meeting of the program "Matter and Technologies" of the Helmholtz Association: 19-06-21
	Towards simulating 2D effects in lattice gauge theories on a quantum computer	CERN Workshop on "Perspectives on Quantum sensing and Computation for Particle Physics": 19-07-21
	SU(2) hadrons on a quantum computer	EPFL Lausanne, Switzerland: June, 2021
	Towards simulating 2D effects in lattice gauge theories on a quantum computer	QuantHEP, Quantum Computation and High Energy Physics online seminar series: June, 2021
	SU(2) hadrons on a quantum computer	CERN "Theory Colloquium": May, 2021
Ashwin Nayak	Rigidity of Superdense coding	Brahmagupta Physics Colloquium, Indian Institute of Technology Madras, Chennai, India: 21-04-21
	Rigidity of Superdense coding	Ohio state Colloquium, Department of Mathematics: 22-04-21
	The Glued-Trees Problem Revisited	Fields institute workshop: Algebraic Graph Theory and Quantum Information at the Fields Institute, Toronto, Canada: 23-08-21
Vern Paulsen	Synchronous Values of Games and the Value Algebra	The 49th Canadian Operator Symposium: 31-05-21
	Cooperative games and entanglement	International Workshop on Operator Theory and its Applications: 19-08-21
	Factorisation and RKHS	Colloquium on Analytic Function Spaces and their Applications, The Fields Institute for Research in Mathematical Sciences: 17-12-21
Micheal Reimer	Secure quantum communication with nanowire quantum dots	University of Stuttgart, Stuttgart, Germany: 29-04-21
	Controlling light at the nanoscale with shaped nanostructures	Global Webinar on Laser, Optics and Photonics (remote): September 25-26, 2021
William Slofstra	Quantum Colloquium – Panel Discussion On The Role Of Proofs In Mip* = Re,	Quantum Colloquium, Simons Institute, UC Berkeley: 04-05-21



	Nonlocal games and sums of squares	American Institute for Mathematics (AIM) workshop on Noncommutative inequalities (hosted online): June, 2021
	Algebras for XOR nonlocal games.	American Institute of Mathematics (AIM) workshop on Non-local games in quantum information theory: Virtual. May, 2021
	The membership problem for quantum correlations is undecidable	University of Innsbruck: October, 2021
	Decision problems for positivity and sums of squares	MFO, Oberwolfach: October, 2021
Adam Wei Tsen	Giant c-axis Nonlinear Anomalous Hall Effect	Magnetic North VII Symposium: 08-06-21
	Giant c-axis Nonlinear Anomalous Hall Effect in T_d - $MoTe_2$	Materials Research Society Spring Meeting: Apr. 21, 2021
	Multifunctional Memristive Switching in 2D Magnets and Charge Density Waves	12th International Conference on Advanced Materials and Devices, Jeju, South Korea: Dec. 8, 2021
	Giant c-axis nonlinear anomalous Hall effect in T_d - $MoTe_2$ and WTe_2	Center for Emergent Matter Science Topical Meeting: Nonlinear Electric and Optical Responses in Quantum Materials, Tokyo, Japan: Mar. 3, 2022
	Multifunctional Memristive Switching in 2D Magnets and Charge Density Waves	6th International Conference on Advanced Electromaterials, Jeju, South Korea: Nov. 10, 2021
Jon Watrous	Applications of Quantum Computing for Data Science	Synthetic Intelligence Forum: 14-04-21
Chris Wilson	Generating Quantum Microwaves Using Superconducting Circuits	Colloquium for IEEE Hyderabad: 2021
	Analog Quantum Simulation of Topological Models with a Parametric Cavity	Colloquium, University of Washington, Seattle, United States: 2021
	Analog Quantum Simulation of Strongly-Coupled Field Theories	BIRS Quantum Foundations, Gravity, and Causal Order, Banff, Canada: 2021
	Giant Artificial Atoms and Programmable Topological Waveguides	Waveguide QED Sicily, Italy: 2021
	Three-Photon Spontaneous Parametric Downconversion in a Parametric Cavity	Colloquium, Chalmers University, Gothenburg, Sweden: 2021
	Quantum Simulation and Computation with Microwave Photons	Physics Colloquium, Purdue University, United States: 2021
	Analog Quantum Simulation of Topological Models with a Parametric Cavity	Quantum Days, Ottawa, Canada: 2021
	Nonclassical Microwaves from Superconducting Quantum Circuits	Colloquium for IEEE Hyderabad, India: 2021
	What Does Quantum Mean?	IEEE Radar 2021, Atlanta, United States: 2021
	Microwave Quantum Optics with Artificial Atoms	Colloquium for Raman Research Institute, Bangalore, India: 2021
Jon Yard	Tight 2-designs in complex projective space	Open Problems in Algebraic Combinatorics, Waterloo, ON: 21-05-21



H. Scientific Visitors & Tours

Visitor Name	Visitor Affiliation
Anja Metelmann	Free University of Berlin
Marcel Tiepelt	Karlsruhe Institute of Technology
John Weeks	Texas A&M University
Priyanga Ganesan	Texas A&M University
Shihan Sajeed	Department of National Defence
Simon Carrier	University of Sherbrooke
Hayata Yamasaki	Institute for Quantum Optics and Quantum Information, Vienna
John Wright	University of Texas, Austin
Luo Laizhen	Harbin University of Science and Technology
Pathompron Jaikwang	Mahidol University
Florian Kanitschar	Technical University Vienna
Giuseppe Bruno	Bank of Italy
Kehui Li	University of Toronto
Yu-Ting Chen	Harvard University
Cody Winkleback	Rigetti Computing
Henry Hunt	University of Chicago
Megan Byres	University of Colorado, Boulder
Jaden Wang	University of Colorado, Boulder
Kate Fenwick	University of Ottawa
Hannah Varekamp	Carnegie Mellon University