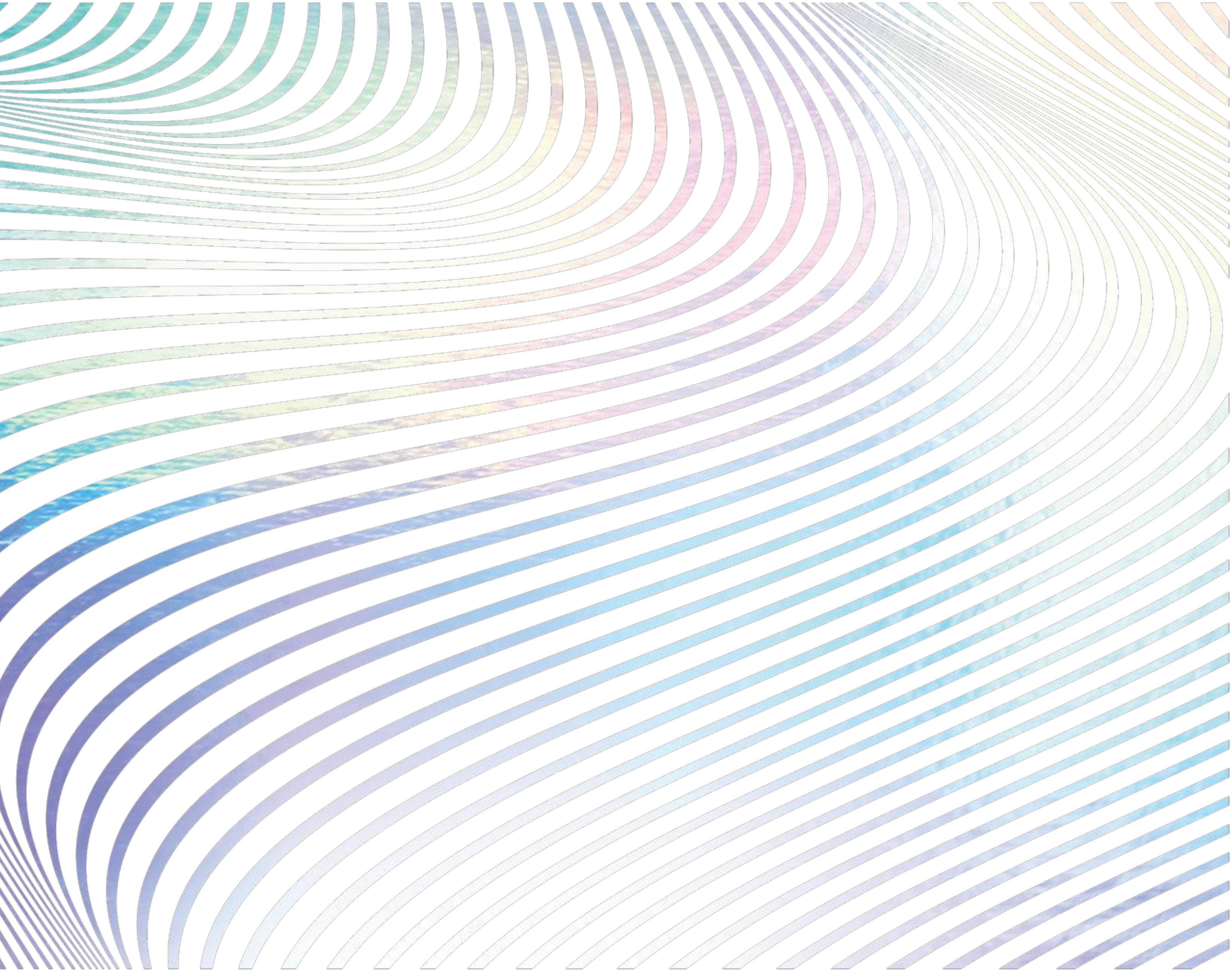
IQC IMPACT REPORT 2019

Institute for Quantum Computing



Institute for Quantum Computing

THE HEART OF THE QUANTUM VALLEY

OUR VISION

Harnessing quantum mechanics will lead to transformational technologies that will benefit society and become a new engine of economic development in the 21st Century.

OUR MISSION

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.

OUR STRATEGIC OBJECTIVES

Training the quantum workforce

Supporting industry

Advancing quantum research and technology

Front cover: A representation of the wave nature held by all quantum objects, when observed in the correct way

CONTENTS

MAKING AN IMPACT

44,149

citations of 1,869 IQC publications since 2002

1,600+

people trained in quantum information and technology since 2002

40%

year-over-year growth of usage of IQC's Quantum-NanoFabrication and Characterization facility (QNFCF) used to test and develop devices since 2014

30%

of IQC faculty are commercializing their research and expertise

650k+

guests through QUANTUM: The Exhibition and Pop-up since 2016

Quantum

CHAMPIONS

ADVANCING QUANTUM

Interim Executive Director message

It is an exciting time in quantum as research, breadth of applications, commercial activity, and general awareness are accelerating together. Researchers at the Institute for Quantum Computing (IQC) are discovering and building quantum technologies that will revolutionize some of the largest industrial sectors in the world: health and medicine, natural resources, environmental monitoring, cybersecurity, electronics, and telecommunications. We are working with industry to develop new ways of solving some of the most challenging problems the world is grappling with today. IQC members have connected quantum to important applications, from communications security to new techniques in cancer treatment.

IQC's vibrant community brings together scientists, mathematicians, and engineers to advance quantum opportunities. We are a magnet drawing world-class talent to Waterloo Region and are training the quantum workforce of the future. This year we welcomed theoretical quantum computing and algorithms expert David Gosset from IBM (read more about Gosset on pg.34). We also attracted Joel Wallman, whose expertise is in characterizing and correcting errors in practical quantum computers.

This was a year of research milestones at IQC with advances across quantum computing, communication, sensors, and materials. We developed new quantum algorithms and methods for optimizing the performance of quantum computers, cooled and trapped Barium and Ytterbium ions for quantum simulation and computation, and expanded the theory of quantum communication and developed new techniques essential for Canada's quantum satellite mission. Finally, we developed new materials for improving both quantum and classical electronics. Select research achievements are covered throughout this report.

Our programs and workshops are developing the quantum workforce. There are roughly 7,000 quantum experts worldwide; over 1,600 people received training at IQC. We have built the most comprehensive graduate program globally in quantum technology, and this year we celebrated our highest enrollment in the institute's history. Our alumni are now working in multi-nationals, startups, government, and academia.

IQC is the heart of Waterloo's Quantum Valley, the technology cluster and the world-leading quantum industrial sector. The Quantum Valley brings academics, start-up companies, incubators, and investors together to accelerate the commercialization of quantum technology. Some of IQC's research achievements form the basis for new commercial opportunities, and over 30% of IQC faculty are actively involved in quantum start-up companies.

IQC's success would not be possible without the generous support from our partners. We gratefully acknowledge the financial support and leadership from the Governments of Ontario and Canada, the University of Waterloo and President Feridun Hamdullahpur, and Mike & Ophelia Lazaridis. Their vision and support have made IQC's incredible growth possible. Together we are building Canada's future quantum economy, right here in Waterloo.

KEVIN RESCH
INTERIM EXECUTIVE DIRECTOR, IQC
PROFESSOR, DEPARTMENT OF PHYSICS AND ASTRONOMY
UNIVERSITY OF WATERLOO

THE POWER OF QUANTUM

Chair of the Board message

The unique principles of quantum mechanics make possible new applications, materials, and transformative technologies that are simply impossible under classical rules. The pursuit of these opportunities is what led us to establish at the University of Waterloo and the other partner organizations in the Quantum Valley. It is this same pursuit that drives the growing number of outstanding researchers at IQC to continue in their research and development efforts.

With access to state-of-the-art facilities and cutting-edge tools (many of which are the first of their kind), IQC researchers continue to advance our fundamental understanding of quantum information science and continue to develop new quantum technologies that will have broad societal value. These efforts are also driving the establishment of a quickly growing number of quantum startup companies in Canada, as more and more global industry players recognize the unique capability of our quantum researchers and entrepreneurs.

I am pleased to announce two new faculty who are joining our roster of world class researchers. Firstly, a former postdoctoral fellow, theorist David Gosset, is returning to IQC as an Associate Professor after working at IBM's T.J. Watson Research Centre. David's fundamental algorithmic research will refine quantum algorithms guided by quantum computers. Secondly, Joel Wallman has been working at IQC since 2013, first as a postdoctoral fellow, then as a Research Assistant Professor. Today, he is an Assistant Professor whose research focuses on simulating quantum systems.

POWERED BY PEOPLE, SOME RECENT ADVANCES BY IQC RESEARCHERS INCLUDE:

- A quantum sensor that outperforms existing technologies and promises significant advancements in long-range 3D imaging and monitoring the success of cancer treatments (Michael Reimer's group);
- A broadband, two-phase grating interferometer technique, paving the way for advances in imagining, material sciences, and quantum research (Dmitry Pushin and David Cory's groups);
- Research that shows certain error correcting codes turn complex coherent errors into much simpler ones. This innovation makes it possible to determine error rates and thresholds and optimize recovery in real-world quantum computers (Raymond Laflamme's group);
- Techniques to allow for direct measurement of entanglement on picosecond time scales, crucial for both understanding the unique features of time-entangled photons and for achieving high-resolution quantum-enhanced measurement in space and time (Kevin Resch's group);
- Research that shows a class of algorithms that outperforms any classical algorithms and is suitable for near-term quantum devices as the circuit depth is constant (David Gosset); and
- New quantum material that shows an extremely large response to a magnetic field and relevant to engineering of quantum technologies (Wei Tsen's group).

Our theorists and experimentalists continue to push towards the development of general purpose quantum computers here at IQC. Our two ion trapping labs, led by Crystal Senko and Rajibul Islam, are successfully up and running. This is the first exciting step in building out quantum simulators and eventually quantum computing applications.

To strengthen innovation and development in this research, matching funds from the University of Waterloo and industry partners including Quantum Valley Investments has resulted in IQC's $140 million Transformative Quantum Technologies (TQT) effort led by Professor David Cory. Key to this has been the defining of a new innovation cycle specifically for quantum and establishing the infrastructure to enable it. With support of CFREF, UW, CFI, and industry, TQT has built a resource that provides a complete implementation of tools for design, fabrication, testing, and deploying quantum technology. This infrastructure attracts quantum researchers, making IQC a growing center for academic and industrial quantum R&D. A new initiative, and key part of the innovation cycle, is the building of quantum simulators. These provide testbeds for understanding both quantum materials and the engineering of quantum devices. Three simulators are currently being deployed and will become shared resources.

The result of these advances is a growing number of exciting new quantum businesses, that in one way or another are connected to IQC. These businesses continue to gain traction with global industry, and attract investment from both strategic investors from around the world and the international venture capital community.

With all of the progress that is being made, it's almost hard to believe that we are only just scratching the surface in terms of what we believe is possible with quantum. There is no doubt that there will be exciting developments in the coming year and in the coming decade for quantum mechanics in a large number of fields. I am both pleased and very proud that IQC and its Quantum Valley partners continue to play a leadership role in this new and exciting global industry.

MIKE LAZARIDIS, O.C., O.ONT., FRS, FRSC
CHAIR, IQC ADVISORY BOARD

QUANTUM MOMENTUM

Chair of the Executive Committee message

Scientists at the IQC are driving the future of quantum research with tremendous momentum.

Although a powerful exploration of quantum physics has challenged and transformed information and technologies in decades past, building the quantum industry is now on the horizon.

Quantum information science is already generating new discoveries in health care, information technology, and security, along with natural resource development, climate, and the environment, but it's the quantum industry that will drive economic growth and development. I look toward this global transformation with certainty that a well-defined vision at IQC is steering the way as researchers embrace this challenge.

IQC's home is in the heart of Canada's Quantum Valley, but a vast and extensive network of partners continues to develop and leverage new opportunities and funding to support infrastructure, build intellectual capacity, and develop new technologies. Seventeen years after the establishment of IQC and amidst a long-term culture at the University of Waterloo that values the discovery of fundamental research, seizes opportunities for transformation, and thrives on collaborative and interdisciplinary research, there's no doubt that this immense research strength will play a leading role.

By harnessing the power of quantum research, together IQC and Waterloo continue to shape the next Quantum Revolution.

CHARMAINE DEAN
CHAIR, IQC EXECUTIVE COMMITTEE
VICE-PRESIDENT, RESEARCH AND INTERNATIONAL
UNIVERSITY OF WATERLOO

QUANTUM BREAKTHROUGHS AND LEADING WITH IMPACT

Message from the President

The world is in the midst of a seismic shift technologically, scientifically, and socially.

The forces at the core of these shifts includes the next generation of computing and there is no doubt that the University of Waterloo and the IQC will continue to be home to the discoveries and opportunities that await from this maturing field of research. The global challenges quantum computing can help us find solutions to are complex in nature. IQC is more than at the forefront of finding these solutions; it is the heartbeat of a thriving Quantum Valley right here in Waterloo, Ontario.

Pushing the boundaries of what is possible is built into our DNA. It drives our curiosity, our dedication to fundamental research, and the power of collaboration. Collaboration is at the centre of IQC as it is home to some of the most brilliant quantum researchers in the Faculties of Engineering, Math, and Science.

It is no easy task to leverage quantum mechanics and harness it for the betterment of our world, and yet, IQC researchers are doing just that and changing the face of science and industry at the same time.

The strides IQC has made in quantum computing continue to reverberate around the world. The industries that are being invented and reinvented by quantum discoveries made at Waterloo are being recognized and lauded by our global peers.

The quantum revolution is upon us and, thanks to the University of Waterloo and IQC, Canada is emerging as the global leader.

FERIDUN HAMDULLAHPUR
PRESIDENT AND VICE-CHANCELLOR
UNIVERSITY OF WATERLOO

FACULTY

Adrian Lupascu
PHYSICS AND ASTRONOMY
Superconducting Quantum Devices Group

Ashwin Nayak
COMBINATORICS AND OPTIMIZATION
Quantum Information and Computation Theory Group

Christine Muschik
PHYSICS AND ASTRONOMY
Quantum Optics Theory

Christopher Wilson
ELECTRICAL AND COMPUTER ENGINEERING
Engineered Quantum Systems Lab

Crystal Senko
PHYSICS AND ASTRONOMY
Trapped Ion Quantum Control

David Cory
CHEMISTRY
Quantum Processors Lab

David Gosset
COMBINATORICS AND OPTIMIZATION

Debbie Leung
COMBINATORICS AND OPTIMIZATION
Quantum Information and Computation Theory Group

Dmitry Pushin
PHYSICS AND ASTRONOMY
Quantum Sensing in Physics

Guo-Xing Miao
ELECTRICAL AND COMPUTER ENGINEERING
Functional Quantum Materials

Joel Wallman
APPLIED MATHEMATICS
Quantum Information and Computation Theory Group

John Watrous
CHERITON SCHOOL OF COMPUTER SCIENCE
Quantum Information and Computation Theory Group

Jon Yard
COMBINATORICS AND OPTIMIZATION
Quantum Information and Computation Theory Group

Jonathan Baugh
CHEMISTRY
Coherent Spintronics Group

Joseph Emerson
APPLIED MATHEMATICS
Quantum Information and Computation Theory Group

K. Rajibul Islam
PHYSICS AND ASTRONOMY
Quantum Information with Trapped Ions

Kevin Resch
PHYSICS AND ASTRONOMY
Quantum Optics and Quantum Information Lab

Kyung Soo Choi
PHYSICS AND ASTRONOMY
Laboratory of Ultracold Quantum Matter and Light

Matteo Mariantoni
PHYSICS AND ASTRONOMY
Laboratory for Digital Quantum Matter

Michael Reimer
ELECTRICAL AND COMPUTER ENGINEERING
Quantum Photonic Devices Lab

Michal Bajcsy
ELECTRICAL AND COMPUTER ENGINEERING
Nano-Photonics and Quantum Optics Lab

Michele Mosca
COMBINATORICS AND OPTIMIZATION
Quantum Information and Computation Theory Group
Quantum-safe Cryptography Group
Qsoft: The Quantum Software Group

Na Young Kim
ELECTRICAL AND COMPUTER ENGINEERING
Quantum Innovation (QuIN) Lab

Norbert Lütkenhaus
PHYSICS AND ASTRONOMY
Optical Quantum Communication Theory Group

Raffi Budakian
PHYSICS AND ASTRONOMY
Nanoscale Magnetic Resonance Imaging Lab

Raymond Laflamme
PHYSICS AND ASTRONOMY
Quantum Error Control and Error Correction
Quantum Information and Computation Theory Group

Richard Cleve
CHERITON SCHOOL OF COMPUTER SCIENCE
Quantum Information and Computation Theory Group

Thomas Jennewein
PHYSICS AND ASTRONOMY
Quantum Photonics Lab

Vern Paulsen
PURE MATHEMATICS
Quantum Information and Computation Theory Group

Wei Tsen
CHEMISTRY
Quantum Materials and Devices Lab

William Slofstra
PURE MATHEMATICS
Mathematics of Quantum Information

RESEARCH EXCELLENCE

300+

vibrant researcher community including 6 Research Chairs, 31 faculty, 150+ graduate students, and 55+ postdoctoral fellows

169+

active grants and awards including an Order of Canada, 47 NSERC-funded grants, 3 Fellows of the Royals Society, 2 CFIs, and 1 CFREF

270+

active collaborations in 2019 spanning 26 countries and 6 continents

100+

invitations to IQC faculty to give quantum talks worldwide

Quantum

SENSING

Using quantum mechanics for new sensors with significant increases in sensitivity, selectivity, and efficiencies.

IMPACT

- Early cancer detection, improved cancer treatment
- Improved geological exploration
- Structural biology
- Defence

THE MELODY OF LIGHT AND MATTER

Quantum mechanic by day, musician by night

PhD student Vadiraj Ananthapadmanabha Rao has a small music studio at home. There, he creates music and records covers of his favourite songs. He especially likes to sing songs from other languages. It gives him a feel for the culture, he says, and allows him to feel immersed in something new and different.

The time he spends at IQC is also dedicated to exploring something new. "The field of quantum physics is still in its early stages, and that's what makes investigating this field so exciting. Everything is new."

CREATING QUBITS

In the Engineered Quantum Systems (EQS) Lab, with faculty member and principal investigator Christopher Wilson, Rao uses superconducting microwave circuits to study the interactions between light and matter to explore new regimes of microwave quantum optics.

"I study the physical effects predicted by theory," explains Rao, an Electrical and Computer Engineering student. "In the quantum world, we look at the smallest unit of matter: individual atoms. [In my lab,] we work with artificial atoms, and this gives us the advantage of engineering different aspects of each one."

The atoms used in the EQS Lab are superconducting electrical circuits, consisting of capacitors that store electrical energy in an electric field, and inductors that store energy in a magnetic field when electric current flows through it. The integral part of the circuit is a tiny device called a Josephson junction, a type of nonlinear inductor.

"We build superconducting qubits using these artificial atoms," said Rao. The Josephson junction-based circuit is the basic element that goes into all of the devices engineered in the EQS Lab. The superconducting qubits behave as two-level systems and, thanks to quantum mechanics, can be in a superposition of states—both 0 and 1—at the same time. This ability gives qubits in superposition robust processing power.

"The interesting question becomes: what can we do with this?"

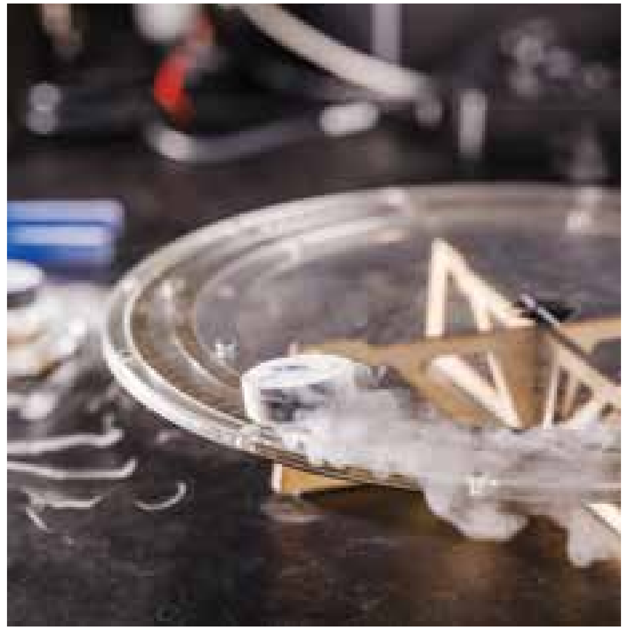
QUANTUM AVANT GARDE

Harnessing the effects of light-matter interactions can be useful in processing quantum information—a task at the heart of many quantum technologies like quantum computers and quantum simulators. Superconducting circuits also have applications in current technologies, like sensors and radar, to improve sensitivity and detectability.

What's most fascinating for Rao, though, is the investigation of a new area of quantum optics. His research pushes boundaries to demonstrate new physics phenomena. For example, expanding a two-level qubit to a three-level qubit system could uncover new technological possibilities beyond the imagination.

The exploration of this unchartered territory of physics is as intriguing for Rao as learning a new language through music. In his home studio, he experiments with tune and pitch to capture a precise emotion with music. In the lab, he tunes the properties of atoms to see different effects of the interaction between light and matter.

Whether it's the creation of music or the construction of a new quantum technology, Rao is a seeker: the process experimental, and the results intriguingly beautiful.



MONITORING CANCER AT THE NANO-LEVEL

How a new quantum sensor could improve cancer treatment

The development of medical imaging and monitoring methods has profoundly impacted the diagnosis and treatment of cancer. These non-invasive techniques allow health care practitioners to look for cancer in the body as well as determine if treatment is working.

But current techniques have limitations; namely, tumours need to be a certain size to be visible. The ability to detect cancer cells, even before there are enough to form a tumour, is a challenge that researchers around the world are looking to solve.

IQC researchers have developed a quantum sensor that is promising to outperform existing technologies in monitoring the success of cancer treatments.

"A sensor needs to be very efficient at detecting light," explained principal investigator Michael Reimer, an IQC faculty member and professor in the Department of Electrical and Computer Engineering. "What's unique about our sensor is that the light can be absorbed all the way, from UV to infrared. No commercially available device exists that can do that now."

Current sensors reflect some of the light, and, depending on the material, this reflection can add up to 30 percent of light not being absorbed.

This next-generation quantum sensor designed in Reimer's lab is very efficient and can detect light at the fundamental limit—a single photon—and refresh for the next one within nanoseconds. Researchers created an array of tapered nanowires that turn incoming photons into electric current that can be amplified and detected.

When applied to dose monitoring in cancer treatment, this enhanced ability to detect every photon means that a health practitioner could monitor the dose being given with incredible precision. Such care would ensure that enough is administered to kill the cancer cells, but not too much that it also kills healthy cells.

Beyond dose monitoring for cancer treatments, the next-generation quantum sensor also has the ability to significantly improve high-speed imaging from space and long-range, high-resolution 3D images.

Reimer is now working on a prototype to begin testing outside of his lab. His goal is to commercialize the sensor in the next three to five years. "I enjoy the fundamental research, but I'm also interested in bringing my research out of the lab and into the real world and making an impact on society," said Reimer.

Adapted from the University of Waterloo's Global Impact Report

Quantum
COMMUNICATION

Developing ultra-secure communication channels and global quantum networks by leveraging the power of the quantum world.

IMPACT

Security, privacy, and cryptography

Satellite-based global quantum networks

PRIVATE COMMUNICATION

A fundamental human right

Former privacy and civil rights lawyer at the Electronic Frontier Foundation, Nate Cardozo explained that the ability to safely and openly communicate is crucial to a free society, and benefits everyone whether one has anything to hide or not.

For Debbie Leung, professor in the Department of Combinatorics and Optimization in the Faculty of Mathematics, it's one of the driving forces behind the work she does in the theory of quantum communication. "Everyone should be given the option to speak privately, to communicate securely," she says.

Communication—the sending and receiving of information—happens constantly. When we make phone calls, browse the Internet, or buy groceries on credit cards, we send some type of data through a communication channel.

The same fundamental process applies to quantum communication, except, thanks to the advantages offered by the quantum channel and quantum data, it is a more secure method of sharing information.

How does it work? A quantum communication channel can be engineered to guarantee privacy by allowing the communicating parties to detect the presence of an eavesdropper, like a hacker. Quantum data cannot be copied, and cannot even be learnt without being corrupted. By this definition, when you send or receive quantum information reliably, you know that no one has learned about the information, since the eavesdropper introduces noise in the data every time they try to steal a peek at the data. When the communicating parties are alerted to the eavesdropping activity, they abort the mission.

This is also what makes quantum communication difficult. That single copy of the information has to make its way from the sender to the receiver; currently, the fragility of quantum states limits this distance.

Leung, with other IQC researchers and collaborators around the world, is working to advance quantum communication, improving its practicality by proposing theoretical methods to make quantum communication more robust, thereby extending the distance that quantum data can travel and contributing to a world in which we can communicate securely.

Protecting our private communication isn't just about keeping our banking information safe. It's preserving our right to share information, learn about the world around us, and make informed decisions for the benefit of society.

EVERY DETAIL MATTERS

Taking quantum to space

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

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

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

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

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

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

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

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

Quantum COMPUTING

Harnessing the quantum behaviour of atoms, molecules, and nanoelectronic circuits for a radically different, and fundamentally more powerful way of computing.

IMPACT

- Security
- Optimization
- Simulation of physical, chemical, and biological processes
- Drug and material design

SOFTWARE

For the quantum age

Imagine if we could remove pollution from the atmosphere, or design drugs targeted for more effective treatment against disease? Poised to revolutionize society, quantum technologies may help us overcome these and other research challenges—and IQC and Department of Physics and Astronomy PhD student Kristine Boone is helping to pave the way.

After almost two decades of research, the first quantum computers are emerging from research labs around the world. Their unprecedented processing power is anticipated to impact areas such as healthcare, transportation, communication, and digital privacy.

Inspired by these possibilities, Boone has set her sights on correcting the Achilles' heel of quantum computing: errors.

A traditional computer uses long strings of bits, encoding information as 0s and 1s. But quantum computers take a different approach. They use quantum bits—qubits—that, thanks to quantum mechanics, can be both a 0 and a 1 at the same time. Known as superposition, this ability to be in two states at once offers powerful computing potential and gives quantum computers an edge in performing some types of calculations more quickly. The catch: qubits are fragile. Any imperfection in the system can cause errors that affect the outcome of a quantum computation.

Recognizing the immediate need for software capable of measuring, mitigating, and correcting quantum errors, Boone's supervisor, IQC faculty member Joseph Emerson, along with assistant professor Joel Wallman, co-founded Quantum Benchmark. Their mission: to enable quantum computers to solve real-world problems.

Boone's research specializes in randomized benchmarking, a series of protocols designed to ensure that quantum operations are, in fact, actually quantum. As a researcher at Quantum Benchmark, she designs algorithms to test the quality of quantum operations, and works with experimentalists to diagnose errors and develop customized software solutions for quantum computing hardware.

"If quantum computing is the gold rush, we are making the picks and shovels," said Emerson, a professor in applied mathematics. "The power and potential of quantum technology is there; the tools to harness it are evolving."

TOMORROW'S ADVANTAGE

While there are many technological hurdles still to overcome, a quantum computer with a genuine performance advantage compared to today's computers would mark a major turning point in the quantum revolution.

"A universal quantum computer would allow us to drive science so much faster," said Boone. "It will take the guess work out of simulation and let us start solving some of those really big, impactful problems."

Once something straight out of the pages of science fiction, the development of a universal quantum computer is not far away, said Boone. "I really believe it's a matter of when—not if. That's pretty incredible."

Adapted from the University of Waterloo's Global Impact Report

TRAPPING POTENTIAL

Simulating quantum systems

If you want to understand planetary motion, you build a computer simulation that models our solar system. If you want to understand the behaviour of a many-body system with quantum phenomena like entanglement, you need quantum simulation.

That's where Rajibul Islam, Principal Investigator of the Laboratory for Quantum Information with Trapped Ions (QITI) and assistant professor in the Department of Physics and Astronomy, comes in. Islam has been at the forefront of experimental research in trapped ions as quantum simulators. He brought that expertise to IQC in 2016, and has since built a lab from the ground up.

Now that he and his group are laser-cooling and trapping ions, Islam is excited to explore and expand the capabilities of this quantum computing platform, potentially clearing a path to a new future of scientific understanding and technological breakthrough.

Trapping an ion—a single, electrically-charged atom—requires an ultrahigh vacuum chamber and a whole lot of lasers. Islam and his team take a tiny amount of the rare earth metal Ytterbium and heat it from a solid straight into a gas. The atoms of gas float into a vacuum chamber where lasers ionize and cool them so the electric field between a set of electrodes can trap them. Once trapped, a high-powered ultraviolet laser can manipulate the ions into different states, assigned values of 0 and 1.

One of the benefits of the ion trap platform is that the atoms are all naturally occurring, free of defects and identical, avoiding some of the challenges of artificial qubits. These ions also have long coherence times, meaning that they keep their "quantum-ness" longer than many other systems.

Simulating more complicated quantum systems on chains of trapped ions may allow unprecedented understanding of chemical reactions and interactions in high-energy physics. "These simulations may open up the possibility of answering very fundamental questions that we cannot even begin to approach right now: questions about the Big Bang, matter and antimatter, the specifics of chemical reactions," said Islam.

A deep understanding of what happens at the subatomic level when chemicals interact could allow fine tuning interactions for greater efficiency. "If you think about it, chemical processes are part of our everyday lives: batteries, fertilizers, power generation. Imagine what we could do for society if all these things were made as efficient as possible."

COOKING UP QUANTUM

A new style of computing

If bits of information are ingredients, then algorithms are the recipes a computer uses to cook a dish—and quantum computing is a new style of cooking.

It is the only model of computation truly distinct from the classical computers we use today. A quantum computer doesn't just run through classical recipes faster; it uses different recipes altogether. There is still uncertainty around quantum, but what is known is that quantum computing will tackle some important problems with unprecedented power.

It is this power and mystery that draws IQC faculty member David Gosset to the field.

Gosset began his PhD at the Massachusetts Institute of Technology (MIT) in 2006 with an undergraduate degree in physics and math under his belt. Computer science was boring to him until his supervisor Edward Farhi brought up a paper that demonstrated how a quantum scattering process could be a quantum algorithm. Once he saw the bigger questions that could be interrogated at the intersection of physics and computer science, Gosset was hooked.

Now at IQC as an associate professor in the Department of Combinatorics and Optimization, Gosset focuses on theoretical quantum computing research.

“Most of what I do is based on mathematical interest,” says Gosset. “But once we do the theoretical work of developing an algorithm, many possible applications may open up.”

The ultimate aim of the field of quantum computing is the development of universal, fault-tolerant quantum computers that can run any algorithm designed for them. Until that dream becomes reality, researchers hope to find uses for early-stage quantum devices that have serious constraints on their coherence times, noise levels, and hardware.

“Much of the field of quantum algorithms is now wondering, what can we do with these devices?” says Gosset. “Some of the impact of my work is guiding the exploration of what we can make them do.”

With new recipes, there’s no telling what we could cook up with quantum.

Quantum MATERIALS

Engineering materials with unique quantum properties for the development of advanced quantum processors and devices.

IMPACT

- Foundation of practical quantum devices
- High-capacity energy storage
- Zero-loss electricity transportation

SEEING THE INVISIBLE

The next revolution in medical imaging

Eight-month old Harriet clocked more than 500 hours in the Quantum-Nano Fabrication and Characterization Facility (QNFCF) before she was even born.

Her mom, postdoctoral fellow Michele Piscitelli, is a self-described nuts and bolts low-temperature experimentalist. Specializing in instrumentation, she has a knack for seeing the invisible—or building the tools that can, at least.

Traditional magnetic resonance imaging (MRI) revolutionized medical imaging and transformed our understanding of the structure and function of biological systems, but is limited to millimeter resolution. Now, a tiny microscope that resembles more of a computer chip is poised to be the next big advancement in medical imaging.

It's a long-term goal that Piscitelli is passionate about. She's spent hours in the QNFCF fabricating the materials and assembling, with nanometer accuracy, the small device that she describes as an "on-chip" MRI scanner.

The device is small, but promises to be mighty. "This work extends the powerful capabilities of MRI to the nanometer scale and provides a whole new lens with which to view the structure and function of complex biomolecules," said Raffi Budakian, lead investigator of the Nanoscale Magnetic Resonance Imaging (NMRI) lab and a professor in the Department of Physics and Astronomy at Waterloo.

To test the device, the NMRI team is experimenting with an inorganic crystal sample. "First, we have to see how well the device is measuring, so we use a sample with a very well-known structure. Once we know it can do this precisely, we can start looking at materials on the nanoscale that we haven't had the capability to image yet."

These materials include biologically relevant samples like virus particles and proteins that cause diseases like Parkinson's and Alzheimer's. Gaining a clear image of what these look like could have an immense impact on medicine, from better treatment to a deeper understanding of complex biomolecules.

For now, Piscitelli continues her work in the orange glow of the QNFCF. She has big dreams for how the small imaging device will change the world Harriet grows up in.

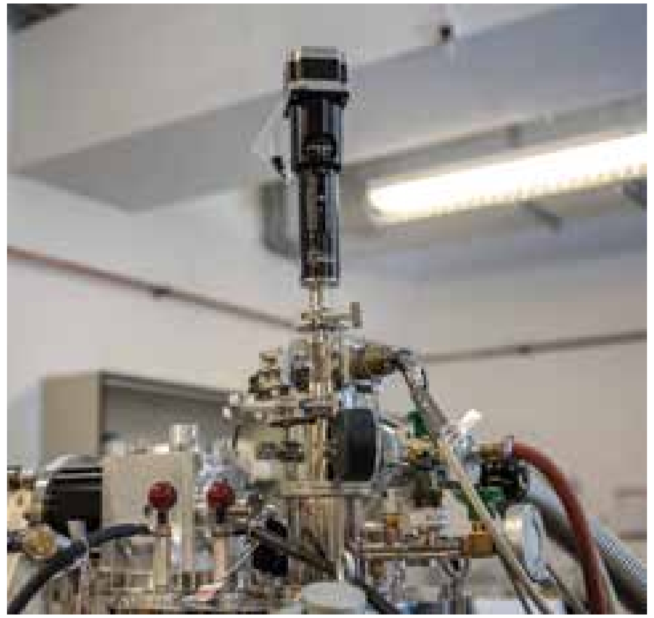
In search of

THE NEXT SILICON

“The researchers that were studying silicon probably did not envision transistors,” said Wei Tsen, principal investigator of the Quantum Materials and Devices (QMAD) lab at the Institute for Quantum Computing (IQC).

The quantum materials studied in his lab could have the same kind of unpredictable—and far-reaching—impact.

There is no hard and fast rule dictating what makes a material quantum, but quantum materials are definitely novel, weird and useful for making new quantum devices. Tsen and his team explore two-dimensional (2D) materials and the exotic magnetic, electronic, or optical properties they exhibit. "We need the right material system to implement new ideas for processing quantum information. Otherwise, it's all theoretical," said Tsen.



In the lab, Tsen and his team start with 2D materials by stripping individual compounds down to the single layer limit. They then recombine these materials, layer by layer, to form a new structure. Tsen described the resulting layered material, called a heterostructure, as "more than the sum of its parts."

"When we combine different 2D materials together to form heterostructures, we might see new phenomena emerge," said Tsen, also an assistant professor in the Faculty of Science's chemistry department. "This is what makes investigating quantum materials so interesting."

By studying special properties that arise in quantum materials, Tsen's research opens new paths for the development of practical quantum devices. The powerful magnetic, electronic or optical properties that could be useful in the design of a quantum device open the door to new applications. Examples include magnetoresistance random access memory (MRAM), high-capacity energy storage and zero-loss electricity transmission.

What the next silicon will be, Tsen cannot yet say. One thing is for sure — it could change our world.

Quantum

TALENT

Fostering the next generation of quantum leaders through programs, training, and outreach.

TRAINING THE QUANTUM WORKFORCE

1,600+ PEOPLE

trained in quantum information and technology at IQC

OFFERING INNOVATIVE TRAINING WORKSHOPS

for talented students and early career researchers to educate and recruit them to IQC

INSPIRING 12,000+

through lectures (academic and public), hands-on training, and interactive quantum demonstrations

650K+

guests through QUANTUM: The Exhibition and Pop-up since 2016

BUILDING THE QUANTUM WORKFORCE

Message from the Quantum Information Graduate Program Director

The world is on the brink of another information technology revolution, this time driven by emerging quantum technologies. It will take a highly skilled workforce to discover innovative applications for quantum technologies that will transform the way we live, work, and play. The Quantum Information Graduate Program at the University of Waterloo prepares students not only to participate in this quantum revolution, but to lead it.

We need well-rounded scientists to tackle the complex obstacles to the next innovations in quantum science. Students in the Quantum Information program are immersed in a multidisciplinary environment integrating seven departments across the Faculties of Math, Science, and Engineering. This diverse exposure equips them with the skills necessary to compete and succeed in a complex quantum economy. A mix of learning through scientific research and advanced courses seamlessly integrates the study of theory and experiment, preparing our students to usher in the next quantum revolution.

This year, IQC graduate students were collectively awarded over 169 separate awards, a testament to the calibre of researchers attracted to the program. The success of our alumni is also a testament to the quality of the program; the graduates of the Quantum Information program have gone on to excel in academia, industry, and government, both within Ontario and around the world.

Our students are the foundation of the breakthroughs happening every day at IQC. Through the exploration of fundamental and applied scientific research, they will help develop the technology—and discover the applications—that will fuel the quantum future.

CHRISTOPHER WILSON
PROFESSOR, DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, CROSS-APPOINTED WITH THE DEPARTMENT OF PHYSICS AND ASTRONOMY
QUANTUM INFORMATION GRADUATE PROGRAM DIRECTOR
INSTITUTE FOR QUANTUM COMPUTING

DEVELOPING QUANTUM LEADERS

IQC graduates and postdoctoral fellows

IQC graduates and postdoctoral fellows are regarded as role models, visionaries, and leaders of the quantum industry, by their peers. Our alumni leave campus and become global citizens who impact academic, industry and government sectors. They inspire future quantum innovators with their passion and intellect and spur quantum advancements in a broad range of fields including banking, communications, space exploration, and technology.

IQC Alumni

SCOTT AARONSON

Postdoctoral Fellow 2007
Professor at University of Texas at Austin, thought leader

ANNE BROADBENT

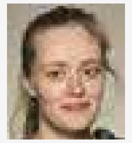
Postdoctoral Fellow 2013
Associate Professor, University Chair at University of Ottawa, IQC Affiliate

DONNY CHEUNG

MA 2002, PhD 2007
Technical Lead Manager at Google

JAY GAMBETTA

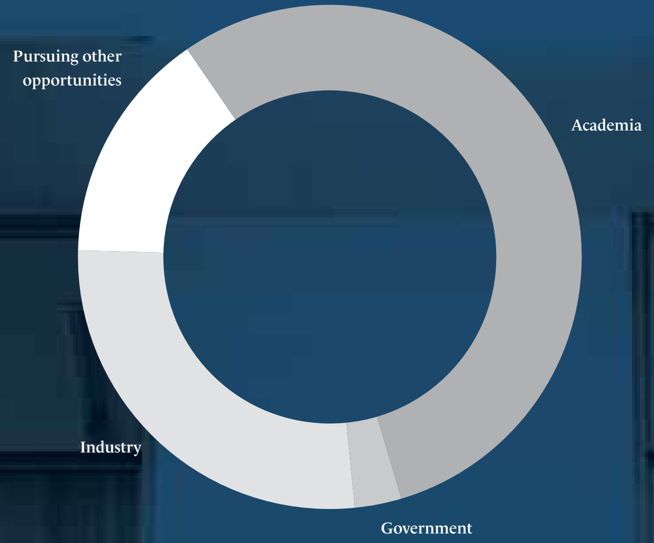
Postdoctoral Fellow 2011
IBM Fellow, Vice President, Quantum Computing at IBM



LAURA MANČINSKA

MA 2009, PhD 2013
Associate Professor, University of Copenhagen

Where are they now?



27%

INDUSTRY

Senior Risk Manager at RBC Capital Markets

Researcher at Fujitsu Laboratories

Co-founder of Single Quantum Systems

5%

GOVERNMENT

Program Director at National Science Foundation

Policy Officer for Canadian Government

Research Officer at the National Research Council

55%

ACADEMIA

Professor at University of Technology Sydney, Centre for Quantum Software and Information

Professor at Université de Sherbrooke

Postdoctoral Fellow at Stanford

Phd Candidate at Massachusetts Institute of Technology

13%

PURSUING OTHER OPPORTUNITIES

RECENT GRADUATES

Forging quantum pathways

THOMAS MCCONKEY

MASc Electrical and Computer Engineering (Quantum Information), '12, PhD '18

Under the supervision of IQC researcher Matteo Mariantoni, Thomas McConkey worked on the development of a scalable 3D wiring, which they named the quantum socket, to overcome one of the scalability problems of superconducting qubits.

Now a Microwave Design Engineer at IBM Q, McConkey says it is the "small nudges" throughout his academic career that have spurred his journey in quantum information science and technology research. He credits his own nudges—reading *The Fabric of Reality* by physicist David Deutsch, joining the IQC community, and connecting with IBM researchers at the APS March Meeting—for steering him towards an industry career path.

COREY RAE MCRAE

PhD Physics (Quantum Information), '17

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

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

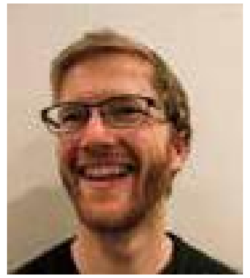
McRae credits IQC for her career preparation in the quantum computing field. "When I started at IQC, I knew very little about quantum computing and quantum information," she said. "IQC provided me with a well-rounded view of these areas and how they fit together, an integral step for a career in quantum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

HELEN PERCIVAL

MASc Electrical and Computer Engineering (Quantum Information), '17

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

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



WILLIAM STACEY

MSc Physics (Quantum Information), '14

William Stacey studied quantum cryptography with faculty member Norbert Lütkenhaus. His research focused on analyzing the security of a Quantum Key Distribution (QKD) protocol, using a trusted third party to extend the distance of performing secure quantum communication to a global scale.

Studying at IQC taught Stacey how to approach new problems that, coupled with strong math skills, he acknowledges is a powerful toolset useful for both academic and industry career paths. It's opened the door for Stacey to pursue his passion as a video game designer working for companies like Behaviour Interactive, Hibernum Creations, Spinpunch Inc. and, most recently, Reflector Entertainment. His career highlight so far was realizing a childhood dream—working with Wizards of the Coast on a *Magic: the Gathering* game.

A FEELING FOR QUANTUM

Directed by outreach

It was a hunch that led Maria Julia Maristany to travel thousands of kilometres from her home in Cordoba, Argentina to attend the Undergraduate School on Experimental Quantum Information Processing (USEQIP) at IQC. It was that same intuition that has shaped her educational path ever since.

Maristany had a tough choice to make: attend USEQIP, or a program in Europe focused on particle physics. That's where the hunch came in. "I felt like USEQIP was very well put together. That it encouraged collaboration. And it felt like I was going to be living with people who could talk about physics during lunch and dinner and before going to sleep, and that's exactly what happened," she said.

Maristany returned to finish school in Cordoba, but she knew she had to come back. Two years later and now a Master's student at IQC, she touts the benefits of USEQIP for anyone looking for an introduction to quantum information science. "I'm living out the obvious advantages of the program," said Maristany. "That you're working with important experts in the field is critical."

One of those experts, Canada Excellence Research Chair Laureate David Cory, took on Maristany as an Undergraduate Research Assistant (URA), and now Raymond Laflamme and John Watrous are supervising her work on discrete time quantum random walks and topological phases for her Master's in Science. These two areas of research are quite distinct, but Maristany values having a broad knowledge base.

To diversify her education even further, she is exploring other aspects of physics at the Perimeter Institute for Theoretical Physics (PI) through their Scholars International program. Maristany also values diversity of people, and it was the international cohort of USEQIP, and IQC in general, that Maristany attributes to a welcoming learning environment and an increased sense of belonging.

Now, Maristany hopes to extend that welcoming feeling through scientific outreach with the Faculty of Science at the University of Waterloo, PI, and IQC.

"With scientific outreach, you can try to encourage kids to pursue science as a career—you don't need to be a crazy, genius Einstein to be able to do it," said Maristany. "For all of those who do not necessarily want to do science as a career, you can help them realize it's still within their reach; they can understand it if they want to, and it can make everyday life better."

Quantum

INDUSTRY

Connecting quantum researchers, entrepreneurs, and investors to advance the commercialization of quantum technology.

QUANTUM-NANO FABRICATION AND CHARACTERIZATION FACILITY

The Quantum-Nano Fabrication and Characterization Facility (QNFCF) is open to academia, the community, industry, and government. QNFCF is committed to supporting research output and offers its members characterized and stable baseline processes, nanofabrication process support, detailed Standard Operating Procedures (SOPs), and outstanding customer service.

The QNFCF, formerly known as the Quantum NanoFab, features a substantial cleanroom that contains ISO 4, 5, and 6 certified process bays, a space for processing of a wide range of materials, and a packaging and device assembly lab for backend processing of fabricated devices. It also has several satellite labs devoted to Focused Ion Beam (FIB) processing, Transmission Electron Microscopy (TEM), clean assembly and other activities.

> "[A CANADIAN TECHNOLOGY COMPANY] STAYED IN ONTARIO BECAUSE OF THE TRAINING AND TOOLS OFFERED BY THE QNFCF. WITHOUT THIS RESOURCE, THE COMPANY WOULD HAVE HAD TO RELOCATE TO THE UNITED STATES TO BE CLOSE TO FABRICATION FACILITIES AT CORNELL OR STANFORD UNIVERSITIES."

TRANSFORMATIVE QUANTUM TECHNOLOGIES

The Quantum Alliance (QA) was launched through Transformative Quantum Technologies* (TQT). QA is a first-of-its-kind collaboration between academia and industry. It will build a quantum R&D community to advance the capability and applications of quantum technologies. It will expand on technologies under development at TQT, and encourage participants to have conversations about the impact of quantum applications on a wide range of industries, including defence, health care, and natural resources.

QUANTUM EXPLORATION SPACE

The Quantum Exploration Space showcases quantum technologies and engages industry partners directly. This facility brings together quantum experts and industry in an interactive environment to facilitate the discovery of quantum solutions to some of the most pressing challenges within industry. The space is outfitted with quantum technologies and staffed with experts to assist groups in their discovery of the impact of quantum.

THE WATERLOO STARTUP ECOSYSTEM

Quantum Benchmark is one of 13 startups that have spun out of quantum research at IQC, a number that continues to grow. Waterloo has a unique concentration of quantum researchers, from theorists to experimentalists, embedded in an entrepreneurial ecosystem. It's a game-changing mix that is moving research from the whiteboard to the lab to the marketplace.

A recipient of $76 million in Canada First Research Excellence Funds, TQT is dedicating seven years and over $144 million to tackling quantum challenges that will drive breakthroughs.

SUPPORTING INDUSTRY GROWTH AND COMMERCIALIZATION

30%

of IQC faculty commercializing their research and expertise through startups

35+

industry partnerships lead to quantum advances in areas ranging from optometry to cancer treatment to oil exploration to next generation display technology

40%

year-over-year growth of usage of IQC's Quantum-NanoFabrication and Characterization facility (QNFCF) used to test and develop devices since 2014

500+

quantum workers supporting a $1.9 Billion ecosystem with IQC at the heart

THANK YOU

Our success is the direct result of our partners and we are seeing firsthand how quantum information and technology development underpins innovation and drives prosperity.

This is a pivotal time in quantum. Continued investment is critical to leverage the talent and capacity developed and the economic benefits quantum technology offers Canada. We look forward to continuing to work with you.

Institute for Quantum Computing
University of Waterloo
200 University Avenue West
Waterloo, Ontario, Canada N2L 3G1
iqc.ca