

Going small in a **big** way



Discovery consists of seeing what everybody has seen, and thinking what nobody has thought.

~ Albert Szent-Györgyi, Nobel Prize winner (Medicine, 1937)

It is said that truth is stranger than fiction. We propose a different version: scientific truth is more amazing than science fiction.

Researchers at the Institute for Quantum Computing are developing ideas and technologies that prescient storytellers like Jules Verne and Isaac Asimov could hardly have imagined.

Even the genius Albert Einstein struggled to accept the quantum concepts and phenomena that IQC researchers now utilize every day.

The workings of the quantum realm — the interplay of atoms, electrons, photons and other infinitesimally tiny particles — provide the blueprint for an information revolution.

Ideas once considered the domain of science fiction — teleportation, for instance, or objects existing in multiple states simultaneously — are being harnessed in next-generation technologies that promise to transform our world.

Ultra-powerful computers, unbreakable cryptography, nanotechnologies of unprecedented precision — these are just some of the discoveries being pioneered through quantum information research.

Welcome to the quantum frontier. Prepare to be amazed.

World-Class Science; World-Class People

- 8 Why Go Quantum?
- 8 Faculty and Research Assistant Professors
- 9 Core Areas of Research
- 10 Understanding Quantum Information
- 12 Making Qubits Work For You
- 14 The Interplay of Theory and Experiment
- 16 In the Lab: Quantum Hardware
- 18 Lighting the Way to Quantum Computing and Communications
- 20 A New Breed of Technologies

SPECIAL FEATURE

Mike & Ophelia Lazaridis Quantum-Nano Centre

22 Building for the Future

A Magnet for the World's Best

- 24 Postdoctoral Fellows
- 28 Sir Anthony Leggett
- 29 Graduate Program
- 30 Meet our Graduate Students
- 32 IQC Alumni
- 32 Awards & Recognition

IQC to the World; the World to IQC

- 34 Scientific Outreach
- 35 Conferences, Workshops & Schools
- **36** Events
- 36 IQC Online
- 38 IQC's Global Reach
- 39 Academic & Scientific Visitors

The Year in Review

- 40 IQC by the Numbers
- **42** Governance, Management & Administration
- 43 Thank You

WATERLOO



Contact us

200 University Avenue West Waterloo, Ontario CANADA N2L 3G1

Phone: 1-519-888-4021 Fax: 1-519-888-7610 Email: iqc@uwaterloo.ca

iqc.uwaterloo.ca



Chair of the Board

IQC's first decade has been tremendously exciting. Since its creation in 2002, the institute has become an international leader in quantum information research, making strides in realizing the vision of what quantum information might mean to the world. The formula for IQC's success is simple to state but challenging to apply: attract the top minds in the field, welcome them into a culture of intellectual excitement rich with opportunities for collaboration, and provide them with the tools they need to conduct leading-edge research. It has been a pleasure for IQC's Board of Directors to see this endeavour come to fruition. Many are contributing to its continuing success, but it could not have happened without the leadership and dedication of Executive Director Raymond Laflamme.

The celebration of IQC's 10th anniversary year is crowned by the institute's exciting and important expansion into the new Mike & Ophelia Lazaridis Quantum-Nano Centre.

This architectural marvel at the centre of the University of Waterloo's main campus is a monument to the vision and generosity of Mike and Ophelia Lazaridis, and to the university's commitment to excellence in research. Its outstanding laboratory facilities will enable IQC scientists to surge ahead to new levels in their research.

IQC continues to recruit top minds from around the world. This year, the institute welcomed research assistant professors Vadim Makarov and Radu Ionicioiu, as well as 10 new postdoctoral fellows, taking the institute's total complement of postdoctoral researchers to 40. IQC welcomed four new faculty members this year: professors Robert Koenig, Matteo Mariantoni, Guo-Xing Miao and

Christopher Wilson. These exceptional scientists bring a depth of expertise and variety of experience that enrich IQC's research capabilities.

I am also pleased to welcome Pearl Sullivan, the University of Waterloo's new Dean of Engineering. I'm sure she will follow in the footsteps of her predecessor, Adel Sedra, whose strong understanding and support of IQC I have always appreciated.

Through teaching and mentorship, IQC researchers nurture the next wave of quantum scientists. Ninety-six graduate students, 31 new this year, studied alongside senior researchers. This young group represents the future of quantum science. They will go on to solve problems that seem insurmountable today, and their own students will not know a world in which quantum information is not pervasive throughout technology.

Research at IQC has also sparked the creation of two start-up companies — a sign that the quest for the quantum computer will produce valuable, practical results along the way.

One company, Universal Quantum Devices Inc., has already made the first sales of its flagship quantum optics product, adding to the University of Waterloo's long tradition of entrepreneurship and innovation.

On behalf of the Board of Directors, I thank the researchers, students and staff for their contributions to IQC, and I look forward to their future accomplishments.

T.A Boy-th

Tom Brzustowski Chair of the Board, IQC

A Message from the

Executive Director

I've heard it said that big things come in small packages, but I like to rephrase it. The very smallest packages — atoms, electrons, photons and other quantum particles — will bring about the next big thing.

The quantum information revolution promises to forever change the ways we work, communicate, play and live. Amazingly, this global revolution is fuelled by particles and forces so incredibly tiny and fragile that merely observing them changes their properties.

Since IQC was founded a decade ago, our researchers have peered ever-deeper into the quantum realm, learning how to control nature's building blocks to develop powerful new technologies. Incredible progress has been made so far, and the pace of this progress is accelerating.

The coming year promises to be IQC's most exciting yet, as the institute has just expanded its research operations into the Mike & Ophelia Lazaridis Quantum-Nano Centre. For quantum research, this facility is - quite literally - the next big thing. The 285,000-square-foot building is remarkable in every way, from its technical specifications to its collaborative spaces and stunning architecture. This truly unique building provides the quiet and low-vibration environment needed to perform cutting-edge quantum experiments. The entire facility is designed to inspire collaboration and attract top researchers from around the world.

IQC's expansion into the new building represents another giant leap in the evolution of the institute. What started a decade ago with a handful of brilliant theorists has grown to become the world's foremost hub of theoretical and experimental quantum information research — with more growth yet to come.

IQC is well on its way to achieving even its most ambitious goals. Research conducted at the institute — whether probing



fundamental questions of quantum mechanics or developing innovative new technologies — is regularly published in leading journals, showcased at prestigious conferences and recognized with national and international grants and awards. Our faculty members share their expertise with postdoctoral fellows and students who come to IQC from every corner of the globe. This next generation of quantum pioneers will develop a deep intuition for the quantum realm and lead the world into the quantum information age.

We believe our breakthroughs should be shared with the government organizations, industry partners and members of the public who support the research. IQC hosts many scientific conferences, workshops and summer schools, and publishes a growing library of literature and videos aimed at sharing quantum science with the world.

We could not have achieved this level of excellence without the vision of Mike and Ophelia Lazaridis. The institute also receives tremendous support from federal and provincial governments, and thrives in the vibrant academic environment at the University of Waterloo.

IQC is establishing Waterloo and Canada as the world's "Quantum Valley." Ultimately, this is happening thanks to the brilliant and curious minds who make great science happen here every day. To all the individuals and organizations whose support and guidance allow IQC to lead the global quantum information revolution, thank you.

Raymond Laflamme

Executive Director, IQC

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.



Overview of IQC

IQC was officially created in 2002, sparked by the vision of Mike Lazaridis, to foster pioneering research into the next revolution in technology — quantum information science. Harnessing the quantum laws of nature promises powerful new advances in fields spanning computing, communications and sensors — and IQC was created to lead this charge.

Throughout history, humans have learned to tame and control natural phenomena — fire, steam and electromagnetism, for example — to improve their lives. IQC is now harnessing nature at its most fundamental level.

Building on the University of Waterloo's long-standing strengths in engineering, mathematics and computer science, IQC quickly recruited world-class researchers in the theory underlying quantum information, providing the nucleus of excellence to attract experimentalists. Today, IQC is a highly successful partnership between the University of Waterloo, the private sector, and both federal and provincial governments.

In just 10 years, IQC has become the world's largest research centre devoted to quantum information science and technology. It has created a unique training program for postdoctoral fellows and students, and is intensifying communication and outreach programs. IQC — and Canada — are becoming internationally recognized as leaders in the global quantum race.

An exciting milestone in IQC's history was the expansion into the Mike & Ophelia Lazaridis Quantum-Nano Centre this year. This remarkable facility features a state-of-the-art cleanroom, cutting-edge experimental infrastructure and innovative spaces designed to foster dialogue between researchers.

It's a simple recipe: attract top scientists, give them the best tools and collaborative opportunities, and breakthroughs will happen. IQC's new headquarters, the MIKE & OPHELIA LAZARIDIS QUANTUM-NANO CENTRE



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.

Strategic Objectives

- To establish Waterloo as a **world-class centre for research** in quantum technologies and their applications
- To become a **magnet for highly qualified personnel** in the field of quantum information
- To establish IQC as the **authoritative source of insight, analysis** and **commentary** on quantum information

The result of a unique and forward-thinking partnership between the private sector, government and academia, the Institute for Quantum Computing is a shining example of the university's tradition of fostering innovation and research excellence. Now headquartered in the new Mike & Ophelia Lazaridis Quantum-Nano Centre, IQC will boldly lead Canada and the world toward a quantum future.

~ Feridun Hamdullahpur, President, University of Waterloo

THIS YEAR

20	Faculty	
----	---------	--

Research Assistant Professors

40 Postdoctoral Fellows

96 Graduate Students

New publications in peer-reviewed journals and conference proceedings

69 Institutions collaborating on joint research projects and publications

154 Visiting scientists

21 Long-term visiting scientists

m IQC Annual Report 2012 | iqc.uwaterloo.ca

World-Class Science:

World-Class People

Why Go Quantum?

Computers keep getting smaller and more powerful, because engineers keep figuring out ways to cram more tiny transistors onto each microchip.

Microchips have doubled in processing power, and halved in size, every two years since the 1950s, as predicted by Moore's Law.

But every law has a limit, and Moore's is no exception.

The miniaturization of transistors will soon reach the atomic scale a realm where the laws of classical physics give way to those of quantum mechanics. At this scale, things can be in a superposition of multiple states simultaneously, or intrinsically correlated by entanglement a counter-intuitive phenomenon even Einstein called "spooky."

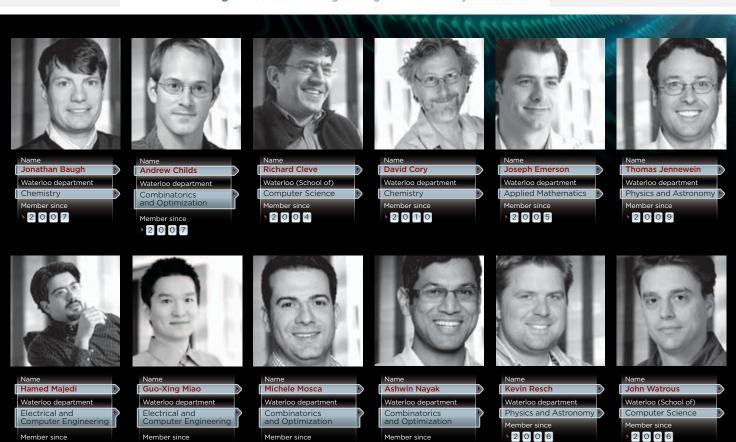
Once considered impediments to computing quantum phenomena have been shown to enable remarkable new information technologies vastly superior to their classical counterparts. Ultra-fast computers, unbreakable cryptography, unprecedented nanotechnology - researchers at IQC aim to unlock the full potential of the quantum realm. Real innovations are already emerging from this research, and we have only begun to envision the scope, power and benefits of quantum information.

The future is quantum.

Faculty

2 0 1 1

IQC's researchers are in the Faculties of Mathematics, Science and Engineering at the University of Waterloo.



2 0 0 2

Co-founder and Deputy Director

2 0 0 5

Core Areas of Research

QUANTUM INFORMATION THEORY

Understanding how to harness quantum mechanical phenomena for computing, communications, sensors and other technologies.

QUANTUM ALGORITHMS

The instructions by which quantum information processors perform computations.

QUANTUM COMPLEXITY

Identifying which problems quantum processors can — and cannot — handle efficiently.

QUANTUM CRYPTOGRAPHY

Providing information security by capitalizing on quantum effects.

QUANTUM ERROR CORRECTION & FAULT TOLERANCE

Understanding how to control quantum systems in the presence of imperfections and imprecision.

SPIN-BASED QUANTUM INFORMATION PROCESSING

Developing quantum processors that use the "spins" of quantum particles such as electrons and atomic nuclei.

NANOELECTRONICS-BASED QUANTUM INFORMATION PROCESSING

The use of nano-scale technologies such as quantum dots or superconducting circuits to implement quantum processing.

OPTICAL QUANTUM INFORMATION PROCESSING

Using the properties of light particles, or photons, to carry and process quantum information.



Name
Robert Koenig
Waterloo department
Applied Mathematics
Member since
2 0 1 2



Name
Raymond Laflamme
Waterloo department
Physics and Astronomy
Member since
Co-founder and
Executive Director



Name

Debbie Leung

Waterloo department

Combinatorics
and Optimization

Member since

2005

Name
Adrian Lupaşcu
Waterloo department
Physics and Astronomy
Member since
2 0 0 9



Name
Norbert Lütkenhaus
Waterloo department
Physics and Astronomy
Member since
2 0 0 6



Matteo Mariantoni
Waterloo department
Physics and Astronomy
Member since
2 0 1 2



Name
Frank Wilhelm
Waterloo department
Physics and Astronomy
Member since
2 0 0 6



Name
Christopher Wilson
Waterloo department
Electrical and
Computer Engineering
Member since

Member since



RESEARCH ASSISTANT PROFESSORS

Name
Radu Ionicioiu
Waterloo department
Applied Mathematics
Member since
2 0 1 1



Name
Vadim Makarov
Waterloo department
Physics and Astronomy
Member since
2 0 1 2



Marco Piani
Waterloo department
Physics and Astronomy
Member since
2 0 1 0



Name
Dmitry Pushin
Waterloo department
Physics and Astronomy
Member since

Understanding

Quantum Information



What is the "Quantum Advantage?"



By Prof. Raymond Laflamme

All computers do one thing exceptionally well — follow instructions. Those instructions are encoded as bits that we typically describe as "one" or "zero."

Over the years, computers have continually become more powerful thanks to the miniaturization of transistors — the "switches" that flip between one and zero. Smaller distances between transistors allow bits to "talk" to each other more quickly. Transistors are getting so tiny, in fact, that they're shrinking down to the atomic scale, where the rules of quantum mechanics come into play.

Computers that capitalize on these laws — quantum computers — have the potential to be incredibly more powerful than even today's most advanced supercomputers.

This boost in processing power arises from uniquely quantum phenomena such as "superposition" — the ability of quantum particles to be in multiple states simultaneously. A computer that uses quantum particles is not limited to processing just two states (one or zero), but rather multiple states simultaneously, allowing the computer to accomplish many tasks at once. Every time a new quantum bit (or qubit) is added to the computer, the processing power can increase exponentially. With this kind of speed-up, a quantum computer could solve problems considered intractable for present-day computers, thus shaking the foundations of computer science.

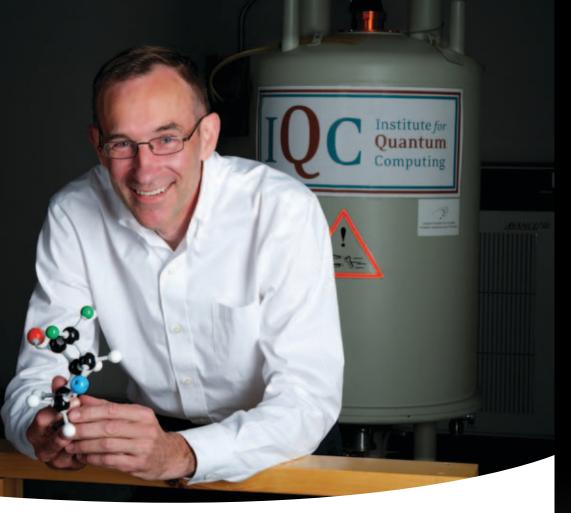




Are we there yet?

Because quantum particles such as atoms and electrons are so incredibly small and sensitive to disturbance, they are not easy to harness and control. Imagine a children's choir — difficult to wrangle and calm down, but the resulting harmony is greater than the sum of its parts. Currently, quantum computing research is aiming to achieve the understanding and control necessary to truly unlock the quantum advantage.

Quantum computers will shine new light on our world, and their importance cannot be overstated. Building the quantum computer remains a long-term goal, but along this path, many new ideas, opportunities and technologies are already emerging. Quantum technologies including sophisticated communications systems and sensors are bursting out of the lab and entering the marketplace. These technologies will enable tremendous advances in materials science, chemistry, physics, geology, medicine and countless other fields. The quantum revolution is well under way, and we're just getting started.





What is an entangled quantum state?

By Prof. Richard Cleve

The quantum world has some counter-intuitive effects — such as events occurring in multiple ways that cancel each other out, and, as a result, not occurring at all (a phenomenon known as interference). Also, in the quantum realm, two or more physical systems can exist in an "entangled" state. Such systems may be very far apart from each other but, nevertheless, there is a sense in which they behave as one single system. This can be described precisely in the language of mathematics.

From the perspective of information processing, entangled systems can be viewed as special kinds of distributed computers — consisting of separate processors that work co-operatively to perform computation. One of the important resources in distributed computing systems is the communication between the processors. It turns out that entangled processors can, in many cases, perform

computations with an enormous reduction in their communication "cost" when compared to processors that do not utilize quantum effects. There are even some remarkable cases in which entanglement causes communication costs to reduce from a large amount to zero (in the language of theoretical physics, these are called Bell inequality violations.)

I have helped develop this distributed computing paradigm in quantum computing. Also, together with my theorist colleagues at IQC — including ANDREW CHILDS, JOSEPH EMERSON, RADU IONICIOIU, DEBBIE LEUNG, NORBERT LÜTKENHAUS, MICHELE MOSCA, ASHWIN NAYAK, MARCO PIANI, and JOHN WATROUS — I have studied quantum entanglement from a variety of other perspectives that have advanced our understanding of quantum computing, quantum cryptography, as well as fundamental physics.

QUANTUM CRYPTO IN THE CLOUD

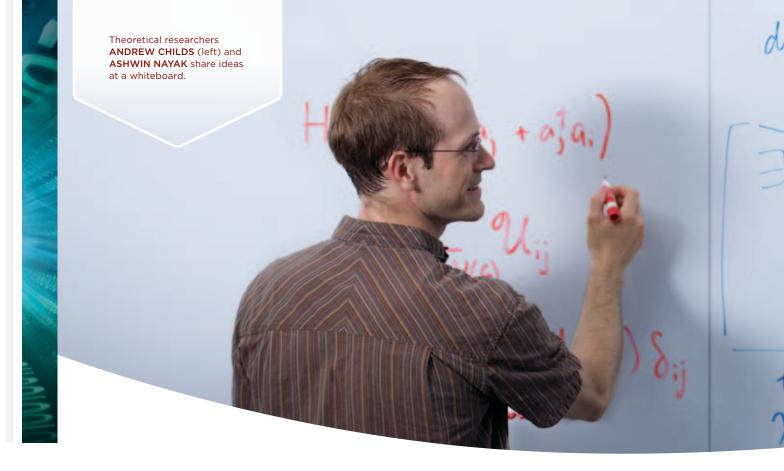
"Demonstration of Blind Quantum Computing," Science, 20 January 2012, Vol. 355

IQC postdoctoral fellow
ANNE BROADBENT was
part of an international
team of theoretical and
experimental researchers
whose work on perfectly
secure "cloud computing"
was published in a January
2012 issue of Science.

The team's breakthrough represents a crucial step toward secure global quantum computing. Because first-generation quantum computers will likely be housed in specialized facilities accessed by remote users, data security will be of paramount importance. Broadbent's work with collaborators in Austria, Singapore and the UK is the implementation of "blind quantum computing," which perfectly safeguards private information in this "cloud" scenario. The information is secure because potential eavesdroppers - and the computer itself - are "blind" to the information being transmitted.

Quard

Did you know that Richard Feynman
was the first scientist to propose putting
quantum particles to work in powerful
new information technologies?



Making Qubits Work For You



How do you "program" a quantum computer?



By Prof. Andrew Childs

Quantum computers have the potential to revolutionize information processing. By representing information quantum mechanically, one can solve a problem by carefully choreographed interference between different computational paths. Using this behaviour, quantum computers can solve some problems significantly faster than ordinary classical computers.

The field of quantum information was kickstarted in 1994 when Peter Shor described an efficient quantum algorithm for breaking integers into their prime factors. The factoring of large numbers, which lies at the heart of modern cryptography, is thought to be intractable for classical computers. Shor's result showed that not only would quantum computers be powerful, but they could have dramatic practical consequences.

However, factoring is only one potential application of quantum computers.

The field of quantum algorithms aims to find new ways to program quantum computers to solve a variety of important problems.

One idea that has recently proven useful for quantum algorithms is the concept of "quantum walks." Whereas many classical algorithms use random walks to explore the space of possible solutions, quantum walks allow quantum computers to explore in *superposition*, sometimes offering a significant performance advantage. Quantum algorithms researchers at IQC have made major contributions to the subject, studying the behaviour of quantum walks on graphs and developing

quantum walk algorithms that dramatically outperform classical computations.

While many potential applications of quantum computers are already known, much work remains. Ongoing research in quantum algorithms seeks to develop new quantum algorithmic techniques and use these techniques to design fast quantum solutions to classically hard problems. Together with my IQC colleagues RICHARD CLEVE, MICHELE MOSCA, ASHWIN NAYAK, and JOHN WATROUS, I pursue new ways that quantum computers can outperform classical ones.



What is quantum complexity?

By Prof. Ashwin Nayak

Whereas the study of quantum algorithms explores what quantum computers can achieve, complexity theory essentially examines how difficult a given computation will be. Some problems can be tackled by a quantum computer exponentially faster than by a classical computer. For other problems, quantum computation provides no relevant advantage.

Simply put, my fellow complexity theorists and I try to find out how "hard" a given problem is for a quantum computer to solve.

For example, IQC's JOHN WATROUS and collaborators achieved a significant breakthrough in 2009 when they resolved a decade-old complexity problem by proving the equivalence of two collections of computational problems (QIP and PSPACE). At the heart of this discovery is the demonstration that a single algorithm can allow us to solve all the problems within QIP (polynomial-time quantum interactive proofs) with exponentially less

space than previously thought possible. The discovery is just one notable example of how theoretical researchers are gaining deeper understanding of the power and potential of quantum algorithms.

Computational hardness could also be an asset, in that we could design a cryptographic scheme that would be as hard to break as solving a hard problem. Present-day RSA cryptography is an example, as its security is based on the hardness of integer factorization for classical computers. Based on similar principles, the complexity of quantum problems could lead to new schemes for secure encryption.

In any challenge, it pays to know what you're up against. With better understanding of the difficulty of computational problems, we can better understand how to approach them.

fitting," Physical Review Letters 109 (2012)

IQC postdoctoral fellow NATHAN WIEBE, with SETH LLOYD (MIT) and DANIEL BRAUN (Université de Toulouse), demonstrated a quantum algorithm that applies to a widely used data analysis technique.

They described an algorithm to improve "least-squares fitting" using a quantum computer. Building upon earlier work that proposed an algorithm for solving linear systems of equations, Wiebe and colleagues adapted it to efficiently estimate the quality of a data-fit without needing to obtain a full solution first, or needing to fully characterize the state of the quantum computer. This would enable rapid searches for simple, accurate approximations to massive quantum data sets.

"It's an enabling tool for subsequent work that could be used to certify the output of future quantum computers," said Wiebe.

The Interplay of Theory and Experiment



IQC TEAM ADVANCES

"Demonstration of Sufficient Control for Two Rounds of Quantum Error Correction in a Solid State Ensemble Quantum Information Processor," Physical Review Letters, 107, (2011)

An advance made by an IQC research team in experimental quantum error correction was showcased on the prominent science website PhysOrg.com. The IQC research team demonstrated a three-qubit error correcting code using the magnetic resonance of carbon nuclei in a single crystal (their results were published in Physical Review Letters). "We've shown that there is the control possible to perform error correction in solid-state systems where the information is encoded on nuclear spins," IQC postdoctoral fellow OSAMA MOUSSA said in the PhysOrg article.

Why pursue theoretical and experimental research?

By Prof. Michele Mosca

IQC theorists and experimentalists pursue a number of different but complementary avenues in the quest to better understand and utilize the power of quantum information.

To fully unlock this quantum power, we must characterize, test, and ultimately control the behaviours of various quantum systems. This involves deep theoretical exploration into the nature of quantum information — such as the research done by IQC professors JOSEPH EMERSON, DEBBIE LEUNG, MARCO PIANI and JOHN WATROUS, among others. This fundamental

among others. This fundamental knowledge underlies a number of methods for controlling and using noisy and not-fully-characterized quantum systems, such as fault-tolerant quantum error correction, quantum control, and protocols for using untrusted quantum apparatus. Experimental testing and implementation of these theoretical concepts leads to their application, and also provides critical feedback and guidance for the theorists.

IQC postdoctoral fellow **ANNE BROADBENT**, for example, conducted the theoretical research underlying a major experimental result achieved by an international team of experimentalists and published this year in *Science*. IQC research assistant professor **VADIM MAKAROV**, meanwhile, performs experimental verification of quantum cryptography systems, while I, along with Prof. **NORBERT LÜTKENHAUS** and others, develop theoretical tools underpinning the testing of untrusted quantum apparatus.

The quantum circuits team I lead with adjunct professor **DMITRI MASLOV** looks at connecting high-level quantum computer programs and algorithms with realistic physical architecture to make the best use of limited quantum computational resources — in other words, the building blocks of a quantum compiler.

Only through the collaborative efforts of theorists and experimentalists can quantum information research as a whole reach its full potential.





What is quantum error correction?

By Prof. Joseph Emerson

IQC researchers, both theoretical and experimental, strive to control the workings of the quantum world — which is easier said than done. Quantum information is very powerful, but also very fragile. In particular, it is susceptible to a process called "decoherence."

Decoherence describes any unwanted process in which quantum information loses its "quantumness" (or its quantum "coherence"). Quantum coherence is what enables superposition — the uniquely quantum phenomenon in which a physical system such as an atom exists in all its possible states simultaneously.

This superposition principle is essential for unlocking the power of quantum information processing. Because quantum bits exhibit superposition, they can be given the values of zero, one, or a superposition of both zero and one, which leads to the quantum speed-up in computation. To preserve and harness superposition, researchers must therefore find ways to reduce and ultimately eliminate the decoherence of physical systems that make up a quantum computer.

Fortunately, researchers at IQC and elsewhere have discovered clever strategies, generally called quantum error correction, to meet the challenge of overcoming decoherence.

Quantum error correction centres around the idea that quantum information can still be recovered after decoherence has occurred, provided the errors are sufficiently mild. Since the implementations of error correction are themselves "noisy," researchers add

secondary protocols to ensure the final operations stay below a certain error threshold, which is the focus of fault-tolerant quantum computing.

Currently theorists and experimentalists at IQC are working on ways to improve existing quantum error correction schemes and identify which schemes are most effective for different physical realizations of quantum information processing. At IQC, my colleagues

DAVID CORY, RAYMOND LAFLAMME,
DEBBIE LEUNG, FRANK WILHELM
and others have all made important
contributions toward understanding and
overcoming quantum errors.

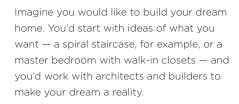




Is there a blueprint for the quantum computer?



By Prof. Jonathan Baugh



At IQC, many of us are trying to build a dream computer: the quantum computer. We have some ideas about what it will do — harness quantum phenomena to accomplish tasks today's computers cannot — but we don't yet know the exact architecture or hardware that will make it a reality. Along with my fellow experimentalists at IQC, I am turning blueprints into lab demonstrations.

Controlling quantum phenomena with the precision needed for computing requires experimentalists to push their setups to extraordinary lengths. IQC's labs are home to a variety of experimental setups, each taking a different approach to quantum information processing, each with its own advantages and challenges. Collaboration is key to solving the big challenges of quantum information processing, which are often beyond the scope of any one particular approach.

The Nuclear Magnetic Resonance (NMR) lab led by **RAYMOND LAFLAMME**, for instance, is one of the earliest and most successful prototypes for quantum computing. Using the same principles that underlie the MRI machine at a hospital, the NMR setup uses the "spins" of molecular nuclei as bits for quantum computation.

Whereas the NMR lab uses nuclear spin, work in my lab aims to harness the spin of electrons. Much of my research involves quantum dots, which are mesoscopic devices that can be considered "artificial atoms," and can be made to hold a single electron. Because they are engineered devices, they can be "tuned" with applied voltages to have desired properties (the atoms provided by

nature don't offer this privilege), and they have great potential to be scaled up into larger systems.

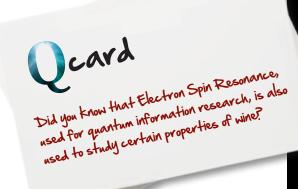
This question of "scaling up" is central to experimental quantum information research. Realizations of quantum bits will only be useful if they can be reliably duplicated many times over and integrated into large processors.

Another promising candidate for scalability is superconducting qubits — the research focus of my colleague ADRIAN LUPAŞCU.

These devices are very small electrical circuits with superconducting elements that exhibit quantum behaviour. Another colleague,

GUO-XING MIAO, is performing leading-edge research at the intersection of spintronics and topological quantum computing.

It's unlikely that future quantum computers will emerge from any one experimental approach, but more likely from a hybrid of several approaches. That's why **DAVID CORY**'s lab at IQC utilizes a broad range of approaches spanning nuclear magnetic resonance, electron spin resonance, optical setups and more. As we continue to draw the blueprint for the quantum computer, we are using all the architectural tools at our disposal.







Lighting the Way to

Quantum Computing and Communications



How is light used in quantum information research?



By Prof. Kevin Resch

Light, whether originating from the sun, a lightbulb or a laser, is made up of tiny particles called "photons." My research aims to harness the unique and fascinating properties of photons for applications spanning fundamental investigations of quantum mechanics and applied research into quantum cryptography and communications.

One of the most important attributes of any quantum system involving light is "entanglement" — the uniquely quantum correlation that exists between particles, even if they are separated by large distances.

Creating entanglement in the laboratory is not easy, but tremendously useful once achieved. For instance, entangled photon pairs are used in creating the cryptographic "keys" for quantum key distribution, a form of ultra-secure cryptography.

Much of the research in my lab is dedicated to generating, detecting and manipulating photons — both single photons and entangled photon pairs. IQC faculty member HAMED MAJEDI conducts related research aimed at developing ultra-sensitive, high-efficiency photon detectors that can be used to measure these photons.

It is hard to imagine quantum communication without light, given that light is the only quantum system to date in which entanglement can be distributed over distances on the 100-kilometre scale. In quantum computation, light will serve as a "bus" or link between separate quantum computers, and may serve as the computer itself.

Quantum sensors harnessing quantum properties of light will produce the most sensitive measurements of fundamental properties, such as position or force. Scientific breakthroughs enhancing our control over light will be crucial to the development of quantum information science in the future.

NEW CHIP ADVANCES OPTICS RESEARCH

"Monolithic Source of Photon Pairs," Physical Review Letters 108 (2012)

A collaboration between IQC and the University of Toronto led to a chip that should greatly advance quantum photonics research. Developed at U of T and tested at IQC, the waveguide chip can perform crucial functions that typically require the large, expensive equipment of an optics lab. The chip enables a new method for creating entangled photons at wavelengths useful for quantum information applications. Such a chip could be integral to the development of scalable photonics-based quantum computers and other quantum technologies, says IQC postdoctoral fellow Rolf Horn, who tested the chip with former IQC professor GREGOR WEIHS. The team's results were published in *Physical Review Letters*, and highlighted in a *Focus* article in the same issue.



In 2004, a group of scientists performed a secure quantum-protected bank transfer through fibre-optic cables installed in the sewers under Vienna.



Can quantum communication go global?

By Prof. Thomas Jennewein

As citizens of the information age, we entrust our most important private data — our banking information and medical records, for instance — to what we hope is unbreakable encryption.

Though most online encryption techniques rely on mathematical problems too difficult for present-day computers to crack, we know that quantum computers will be powerful enough to break these codes. This is one of the chief motivations of quantum cryptography — the use of quantum phenomena to make codes that are impossible to break (even by a quantum computer).

A number of my IQC colleagues
— including RICHARD CLEVE,
DEBBIE LEUNG, MICHELE MOSCA
and ASHWIN NAYAK — have
made pioneering contributions to
quantum cryptography in areas
including quantum fingerprints and
quantum money. Research assistant
professor VADIM MAKAROV tests
quantum cryptography hardware for
vulnerabilities with the aim of certifying
the security of these systems.

My research focuses on the possibility of a secure global quantum communications network connected by satellite.

Quantum cryptography is among the first real-world technologies to have already emerged from quantum information research. One branch of quantum cryptography, Quantum Key Distribution (QKD), is already being used in real-world communications - including a secure link that spans several kilometres over Waterloo. QKD protects private data because of a fundamental quantum law: any observation of a quantum system alters it. That means that eavesdropping on a quantum "key" is detected before any private data is exchanged; only a key that bears no such "fingerprint" is used to encode private information.

QKD is a wonderful tool for ensuring data security, but there's a problem — after traveling about 200 kilometres through fibre-optic cable, the photons used to make the "key" are scattered and no longer useful.

To create global quantum communications networks, we need a way to overcome these distance limits. The solution: send our equipment into orbit on a satellite. I am working closely with IQC colleagues RAYMOND LAFLAMME and NORBERT LÜTKENHAUS to determine the feasibility of a quantum-encrypted global communications project. Experts from the universities of Waterloo, Toronto and Calgary, along with Perimeter Institute and government agencies, are working together on this innovative project.

Although a link-up of this kind will require incredible precision — photons sent from earth will need to reach a fast-moving satellite many kilometres away — we've determined that it can indeed be done. We envision full-scale networks connected by satellite and fibre-optics, protected by quantum cryptography.





Are quantum devices being developed now?

By harnessing quantum mechanics, researchers are trying to build devices that achieve the maximum efficiencies afforded by the laws of nature.

Devices based on quantum mechanics are not necessarily new. Some have been around since the last century, such as magnetic resonance imaging (MRI), transistors and lasers. But the new generation of technologies being researched and developed through quantum information science aim to harness the full power of quantum mechanics.

While a full-scale quantum computer is still a long-term goal, researchers are now building devices based on quantum information principles — devices that have the potential to

be vastly superior to their classical counterparts, and could have important applications across many fields.

Prof. **DAVID CORY**'s work is largely focused on the spin properties of quantum particles. Think of spin as a small bar magnet — the smallest allowed by nature. Cory and his team aim to achieve sufficient control of quantum systems to build spin-based information processors and sensors.

Progress is being made every day. Quantum sensors now under development, for example, will likely have near-term applications in chemistry, such as advances in thin-film samples — a process important to medicine and materials science.

Cory's lab is equipped with a wide range of experimental equipment — nuclear magnetic resonance, electron spin resonance, optics and low-temperature setups — all with the goal of detecting, measuring and controlling quantum systems with ever-greater accuracy.

Cory, **DMITRY PUSHIN** and their colleagues investigate a broad range of approaches to quantum technology, because the power of future quantum computers will almost certainly come from hybrid structures that capitalize on the best aspects of each.



From Discovery to Innovation

Quantum information science continues to move from pure research toward practical, commercially available devices. Patents and spin-off companies are already emerging from IQC research — a trend that will surely accelerate alongside the pace of discovery.

IQC's first spin-off company, *Universal Quantum Devices Inc.*, made its first sale in the spring of 2012. The company's signature product, a novel logic unit conceived by UQD co-founder and IQC faculty member **THOMAS JENNEWEIN**, is a multi-purpose device that accomplishes many tasks central to quantum optics research.

In June 2012, the institute presented a full-day workshop called *Quantum Entrepreneurship*, aimed at preparing researchers to enter this emerging quantum marketplace. Board Chair **TOM BRZUSTOWSKI** encouraged IQC students to make their own unique contributions to Canadian innovation and prosperity. IQC postdoctoral fellow **ROLF HORN**, himself a quantum entrepreneur who has launched a start-up company called *QuSpin* (which specializes in quantum photonics waveguide chips), described his experiences in the relatively uncharted territory of quantum entrepreneurship.

IQC-NIST
COLLABORATION
YIELDS ADVANCE
IN SENSORS

"Experimental realization of a decoherence-free subspace in neutron interferometry," Physical Review Letters 2011

Researchers at IQC and the National Institute of Standards and Technology (NIST) made an advance in quantum sensor technology that could have widespread applications in industry.

The team pioneered a new approach to neutron interferometry, which can be used to measure properties of sample materials. Previously, the technique was hindered by its sensitivity to vibrations, requiring experiments to be shielded inside a massive blockhouse. The advance by IQC researchers DAVID CORY and DMITRY PUSHIN, and NIST researcher MICHAEL HUBER, was to make the interferometer much more resistant to such disturbance. Inspired by work in quantum error correction, they added a fourth blade to the interferometer, which effectively cancels out the disturbances that plagued standard three-blade interferometers. The modified interferometer can be set up closer to the source of neutrons, allowing for faster and more accurate generation of data.

Mike & Ophelia Lazaridis

Quantum-Nano Centre

Building for the Future

It takes a visionary to
look beyond what's
happening now and to
imagine what's possible
for the future. Mike
and Ophelia Lazaridis
are visionaries whose
forward-thinking
philanthropy made
possible the Institute for
Quantum Computing and
the breakthroughs it
has achieved.

IQC Executive Director, Raymond Laflamme IQC is at the forefront of quantum information processing research, making the University of Waterloo one of the world's premier destinations in the field. The opening of the Mike & Ophelia Lazaridis Quantum-Nano Centre will enable leading-edge multidisciplinary research through the collaboration of nanotechnology and quantum experts working side by side. With this unique combination of strengths from science and math to engineering, the opportunities for designing and developing novel components to build miniaturized devices with extraordinary capabilities are virtually endless.

Pearl Sullivan, Dean, Faculty of Engineering

The centre will help bring the best minds to study small things and produce big results.

Dalton McGuinty, Premier of Ontario



Mike & Ophelia Lazaridis

Quantum-Nano Centre

The Institute for Quantum Computing is celebrating a decade of discovery, and has taken another giant leap in its evolution with the opening of the Mike & Ophelia Lazaridis Quantum-Nano Centre.



1999 2001 2002 2003 2004

- Aiming to build upon the University of Waterloo's internationally recognized strengths in mathematics and computer science, MICHELE MOSCA forms the first quantum information group at the University of Waterloo
- MIKE and OPHELIA
 LAZARIDIS pledge
 support for a
 quantum information
 research institute
 at the University
 of Waterloo
- The University of Waterloo and the Perimeter Institute work together to recruit RAYMOND LAFLAMME from Los Alamos National Laboratory; he becomes IQC's founding Executive Director
- November 27, 2002 the Institute for Quantum Computing celebrates its official opening as a research institute housed in the University of Waterloo's Physics building
- MIKE and OPHELIA LAZARIDIS
 make first personal donation
 of \$3 million to help kick start
 research efforts at IQC. The
 contribution is matched by
 the Canadian Foundation for
 Innovation and the Ontario
 Innovation Trust
- Prof. ASHWIN NAYAK joins IQC

- The Canadian
 Institute for
 Advanced
 Research
 (CIFAR) launches
 its Quantum
 Information
 program led
 by RAYMOND
- ➤ IQC launches outreach efforts inviting local high school students to tour labs

LAFLAMME

- Faculty members ANDRIS

 AMBAINIS, RICHARD

 CLEVE and GREGOR

 WEIHS join IQC
- DAVID POULIN, IQC's first PhD student, graduates from the University of Waterloo
- The institute expands to B.F. Goodrich building
- MIKE and OPHELIA
 LAZARIDIS make
 donation of \$30 million
 to support research at
 IQC, and work with the
 University of Waterloo
 to secure further funding
 totalling \$100 million

The Mike & Ophelia Lazaridis Quantum-Nano Centre opened in September 2012. Constructed to the most stringent scientific standards — including controls for vibration, temperature, humidity, electromagnetic radiation and more — the facility enables quantum information research at the highest international level. The ultra-sterile cleanroom/fabrication facility, for example, is constructed upon a separate foundation from the rest of the building, ensuring that it will never vibrate more than a micron (a fraction of the width of a human hair).

The building is an architectural marvel designed to inspire awe and spark collaboration — essential ingredients in exploring the quantum frontier. A magnet to Waterloo, it will attract the world's top scientists and foster the next wave of quantum breakthroughs.

IQC's first decade saw tremendous growth and research excellence; the next decade and beyond will see quantum science emerge from the labs as practical technologies that will greatly benefit society.



Faculty members JOSEPH
EMERSON, DEBBIE LEUNG

and **HAMED MAJEDI** join IQC

2005

- MIKE and OPHELIA LAZARIDIS
 donate more than \$17 million to
 IQC research at the University
 of Waterloo \$12.5 million of
 which serves as initial funding
 for Quantum-Nano Centre
- JONATHAN BAUGH implements algorithmic cooling in solid-state NMR

Faculty members NORBERT
LÜTKENHAUS, KEVIN RESCH, JOHN
WATROUS and FRANK WILHELM
join IQC

2006

- IQC-led team achieves long-standing world record for universal control of largest number of quantum bits (12) used for computation
- The Canadian Foundation for Innovation and the Ontario Research Fund grant \$36 million to IQC and the Waterloo Institute for Nanotechnology for the construction of a fabrication facility; the University of Waterloo also contributes \$13 million
- Canada's quantum research network, QuantumWorks, launches under the leadership of RAYMOND LAFLAMME

- MIKE and OPHELIA LAZARIDIS continue to support research at IQC with a pledge of \$50 million, inspiring contributions from the Province of Ontario (2006) and Industry Canada (2009), each valued at \$50 million, totalling \$150 million
- IQC and Perimeter Institute collaborate for month-long conference, "Taming the Quantum World"
- Faculty members ANDREW CHILDS and JONATHAN BAUGH join IQC
- ➤ PHILLIP KAYE, RAYMOND LAFLAMME and MICHELE MOSCA publish respected textbook An Introduction to Quantum Computing
- IQC hosts Open House and panel discussion with internationally renowned scientists Sir ANTHONY LEGGETT, GILLES BRASSARD,
 PETER SHOR and RAYMOND LAFLAMME (MIKE LAZARIDIS moderates)
- Nobel Prize winner Sir ANTHONY LEGGETT delivers his first annual summer lecture series at IQC as the Mike and Ophelia Lazaridis Distinguished Research Chair



- Groundbreaking of the Mike & Ophelia
 Lazaridis Quantum-Nano Centre
- ► IQC expands into Research Advancement Centre I (RACI)
- Design and construction of the RACI cleanroom begins
- Inaugural year for IQC's Quantum Cryptography School for Young Students (QCSYS)
- KEVIN RESCH develops a new type of interferometer inspired by quantum entanglement properties
- GREGOR WEIHS and CHRIS ERVEN build a quantum cryptography prototype
- IQC hosts public open house and lecture

- Faculty members THOMAS

 JENNEWEIN and ADRIAN LUPAŞCU

 join IQC
- The Quantum Tamers: Revealing our Weird & Wired Future wins top prize at the Parascience Film Festival JOSEPH EMERSON and RAYMOND LAFLAMME serve as scientific advisors for the documentary
- ANDREW CHILDS demonstrates how to compute using quantum walks
- Inaugural year for IQC's
 Undergraduate School for
 Experimental Quantum Information
 Processing (USEQIP)

- ➤ DAVID CORY joins IQC as Canada Excellence Research
 Chair in Quantum Information Processing supported by
 federal funding of \$10 million over seven years
- IQC expands into Research Advancement Centre II (RACII)
 funded by IQC's benefactors MIKE LAZARIDIS and
 DOUG FREGIN
- JOHN WATROUS and collaborators win best paper award at STOC conference for QIP=PSPACE breakthrough
- IQC welcomes more than 800 visitors to annual open house and public lecture by **DAVID CORY**
- The University of Waterloo and IQC launch the collaborative graduate studies program in quantum information
- Prof. STEPHEN HAWKING is welcomed by University of Waterloo President FERIDUN HAMDULLAHPUR for a special tour of IQC
- IQC postdoctoral fellow ROLF HORN and student CHRIS ERVEN launch IQC's first spinoff company, QuSpin, specializing in quantum photonics wave guide chips

MIKE & OPHELIA LAZARIDIS QUANTUM-NANO CENTRE QUICK FACTS

285,000 square feet, shared between the Institute for Quantum Computing and Waterloo Institute for Nanotechnology

Meets highest scientific standards for control of vibration, humidity, electromagnetic radiation and temperature

Shared cleanroom/fabrication facility enables design of structures billionths of a metre in size

Labs constructed **underground** to minimize electromagnetic interference and vibration

Highly convertible "mind spaces" accommodate conferences, public lectures and more

Auditorium with multi-tiered retractable seating splits into two or four rooms to accommodate up to 220 people

Six-storey atrium with floating staircase provides common ground for scientists of all disciplines to meet and collaborate

An architectural marvel at the heart of campus

Vertical windows of varying reflectivity/transparency on IQC side metaphorically signify quantum superposition; **honeycomb pattern** on WIN side represents strong natural nanostructures





Mike & Ophelia Lazaridis Quantum-Nano Centre

2011

- THOMAS JENNEWEIN launches a program with the Canadian Space Agency that will use satellites for quantum communication
- IQC postdoctoral researcher ANNE BROADBENT co-organizes first annual "Women in Physics" conference with the Perimeter Institute
- IQC launches Quantum Frontiers Distinguished Lecture Series hosting renowned speakers including DON EIGLER, RALPH MERKLE, DAVID WINELAND, LOUIS TAILLEFER and CHIP ELLIOTT
- IQC celebrates 10 years as a world-leading research institute at the University of Waterloo and continues its rapid expansion and ambitious research agenda

2012

- First graduates of the collaborative graduate studies program in quantum information
- Grand Opening of the Mike & Ophelia Lazaridis
 Quantum-Nano Centre
- ROBERT KOENIG, MATTEO MARIANTONI, GUO-XING MIAO and CHRISTOPHER WILSON join IQC as faculty
- A spinoff company led by IQC researchers, Universal Quantum Devices Inc., makes the first sale of its signature product, a multi-purpose tool for quantum optics research

A Magnet for the World's Best Postdoctoral Fellows

Working alongside IQC's faculty and students are 40 postdoctoral fellows who represent the next wave of leaders in quantum science. In the coming pages, a few of these postdoctoral fellows share their perspectives on life, research and IQC.



Anne Broadbent CIFAR JUNIOR FELLOW

For me, solving a math problem is like putting together a jigsaw puzzle. Sometimes, everything works out well and the pieces come together perfectly. Other times, I aim to solve one puzzle, but magically end up with a result that is even more beautiful and amazing than what I set out to create. But often it feels like some pieces of the puzzle are missing: is there really a solution, or should I move on to a different puzzle?

This is when living on our country farm makes a big difference for me. After a day of deep reflection and abstract thinking, I like to work on something a bit more tangible, like tending to the sheep and goats. And guess what: solutions often dawn on me while I'm working in the barn, almost as if my brain needs to go back to neutral before switching to the next gear.

Right now, I am growing a vegetable garden and helping my husband raise our farm animals. I love my research job and find it very rewarding, but when I am stuck on a tough puzzle, it's the short-term sense of satisfaction that comes from growing a tasty tomato or tending to a herd of sheep that keep me going.

POSTDOCTORAL FELLOWS 2012

Gorgan Alagic Mohammad Ansari Mustafa Bal Olaf Benningshof Dominic Berry

Anne Broadbent Jianxin Chen

Lin Chen Chris Erven

Motohisa Fukuda

Silvano Garnerone

Oleg Gittsovich

David Gosset

Patryk Gumann

Gus Gutoski **Brendon Higgins**

Rolf Horn Tsuyoshi Ito

Zhengfeng Ji

Piotr Kolenderski

Eduardo Martin-Martinez

William Matthews

Seth Merkel

Rajat Mittal

Hamid Mohebbi

Osama Moussa

Mustafa Muhammad

Florian Ong

Robert Prevedel

Emily Pritchett

Robabeh Rahimi Darabad

Aiden Roy

Krister Shalm

Urbasi Sinha Yipu Song Jon Tyson Nathan Wiebe Zizhong Yan Bei Zeng

Jingfu Zhang

Eduardo Martin-Martinez

BANTING POSTDOCTORAL FELLOW

Since childhood I have been fascinated by the biomedical sciences, even though I always knew I wanted to be a physicist. I thought that by studying physics I could find precise answers to my most fundamental questions.

Although physics did indeed provide me with answers about the universe, it has also taught me that in the 21st century we still don't fully understand every complex system, including an extremely important one - life.

I am used to doing science in a very mathematical and formally rigorous way: as a physicist, I understand how the difficulty of describing a physical system grows with its complexity.

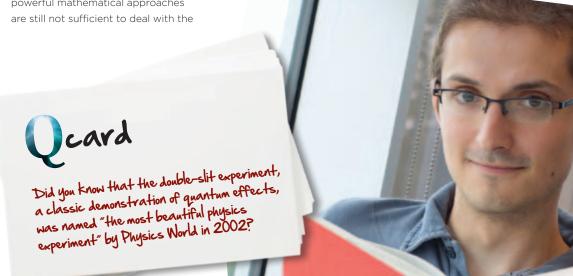
With time, I have accepted that our most powerful mathematical approaches

tremendous complexity of all living beings. That's what continues to intrigue me about the biomedical sciences. In the dense jungle of complexity, beyond the scope of mathematical rigour, biomedical scientists not only understand the workings of life, but they save lives.

I remember my grandmother telling me, when I was 10 years old, that I would never have existed if my father hadn't received life-saving antibiotics for pneumonia. I have since debated questions of life with doctors, biomedical scientists and biologists, and the conversations are always fascinating. In my studies of how quantum phenomena

are interlaced with the structure of space-time, I'm inspired by how other scientists tackle other types of complex problems.

I recently had the good fortune of becoming a Banting Postdoctoral Fellow - a fellowship named after the man who discovered insulin. Being included in this fellowship program is an enormous privilege. I cannot help but hope that in a not-so-distant future, physics and medicine will not be considered completely separate disciplines, but will rather enrich and inform each other through their shared approaches to knowledge.



Postdoctoral Fellows continued

Brendon Higgins

BANTING POSTDOCTORAL FELLOW

Superposition is undeniably cool. Something existing in two different states simultaneously is fascinating and weird, and I love being able to play with that idea in different contexts — polarization (horizontal vs. vertical), energy (ground vs. excited state), or species (human vs. wolf).

One of my more obscure hobbies takes place in a fictional fantasy multiverse full of hybrid animal-people of various shapes, colours, species and creeds. I'm a fan of what's known as anthropomorphic or "furry" artwork — drawings, paintings, cartoons and stories that feature creatures possessing both human characteristics (intelligence, speech, facial expressions and bipedal motion)

and animal characteristics (physical features like fur, ears and tails, as well as temperament).

Anthropomorphic art goes back millennia, but the modern furry fan community began as an offshoot of the science fiction fan community, and it continues to possess similarities with that and other genres — anime and comic book fandoms. It has websites, fanzines, and even conventions where fans meet, exchange stories and art, dress in costume, and generally have an awesome time (Toronto held such a convention in March — it was a riot).

Within the furry community, it's more than just the fictional characters that profess this "superpositional" existence: many fans even represent "themselves" as anthropomorphic animals. For some it's a mask, while for others it's just a fun way of expressing themselves. In either case, engaging with this community and its art is a bit like performing a change of basis: you have to think in terms of superimposed properties, both human and animal, that make up these characters. "Human or animal?" is simply the wrong question to ask. And, similarly to a quantum superposition, its answer can be unpredictable.

For me, entering this strange superposition world — undergoing the change of basis — is a fun and fulfilling transformation.



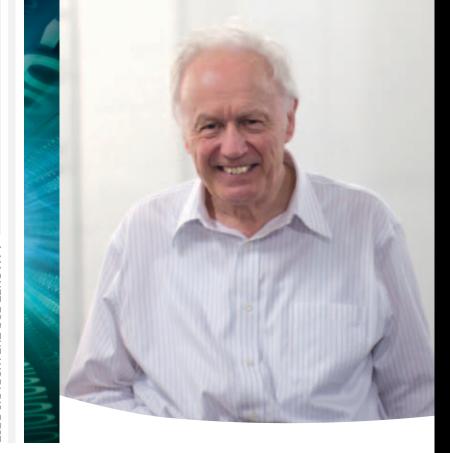


Florian Ong

Hanging out every day amid quantum stuff is thrilling and mentally nourishing, but spending so much time questioning the infinitely small with complex machinery can become somewhat overwhelming. I need to counterbalance these elusive, highly technical pursuits with more grounded, tangible activities, which typically involve wide-open spaces, human locomotion and a good deal of sweat. For instance, just before arriving in Waterloo, I spent two months hiking across the Alps, from southern France to Slovenia, with a tent, silence and wildlife as my only company. This was the best thing my mind and body could have imagined after a few years in a different quantum environment.

Now in southern Ontario and still in the process of exploring how the human body can relate to time and space, I have turned to endurance sports in general, and duathlon in particular (as a pathetic swimmer, the doors of triathlon competition are unfortunately shut to me). I've started running rather recently, and I've always been an enthusiastic bicycle commuter. But the idea of doing both in organized racing events was totally new when I signed up for my first duathlon last summer. I was hooked immediately and did it again and again, increasing the distance, pushing the limits further and further.

Although this call partly arises from a need to escape the confinement of the lab, achieving goals in duathlons, or any outdoor adventure, requires many traits also necessary in my everyday work: dedication, patience, perseverance, passion, and sometimes self-sacrifice. But above all, whether I am running across mountains or squeezing microwave photons, I don't do it with a specific or pragmatic purpose in mind. Rather, I'm pursuing the beauty and harmony of nature in a selfless and maybe absurd quest. To quote Cyrano de Bergerac, "C'est bien plus beau lorsque c'est inutile."



IQC's Laureate in Residence: Sir Anthony Leggett

Sir Anthony Leggett, Nobel Prize-winning physicist, arrives at IQC by bicycle on a sweltering morning — a daily tradition for the past six summers.

Sir Leggett — or Tony, as he is known to his friends and colleagues at IQC — spends every summer lecturing and researching in Waterloo as the Mike and Ophelia Lazaridis Distinguished Research Chair.

Leggett deeply values the relationships he has built in Waterloo. He keeps his mind — and his office door — open to new ideas and collaborations. IQC is honoured to host the Nobel Laureate each year — and the honour, Leggett insists, is mutual.

"IQC has established itself as the leading institution in the world in quantum information," says Leggett, who is based at the University of Illinois at Urbana-Champaign.
"It's stimulating to make contact between my personal expertise — mainly in condensed matter physics and quantum foundations — and the exciting developments in quantum information science."

Leggett was one of three physicists to share the 2003 Nobel Prize in Physics for important contributions to low-temperature physics and superfluidity. He is deeply interested in IQC research, and expects it will lead to "something so exotic we have not dreamed of it yet."

"Just don't ask me what that would be," he adds. "If I knew, I'd be doing it!"

GRADUATE STUDENTS 2012

Matthew Amy

Elena Anisimova Razieh Annabestani Juan Miguel Arrazola Jean-Philippe Bourgoin Steven Casagrande **Grant Cleary** Alessandro Cosentino **Daniel Criger** Pierre-Luc Dallaire-**Demers** Chunqing Deng John Donohue Amin Eftekharian Chris Erven Agnes Ferenczi Chris Ferrie Kent Fisher Joshua Geller Naimeh Ghafarian Kaveh Gharavi MirMotjaba Gharibi Sevag Gharibian Nickolay Gigov Luke Govia Christopher Granade Matthew Graydon Peter Groszkowski **Nupur Gupta Holger Haas** Deny Hamel Fatin Haque Aimee Heinrichs Ian Hincks Tyler Holden Catherine Holloway **Gregory Holloway** Amir Jafari Salim Stacey Jeffery Tomas Jochym-O'Connor Artem Kaznatcheev Mohsen Keshavarz **Botan Khani** Milad Khoshnegar Shahrestani Nathan Killoran Feyruz Kitapli Vadym Kliuchnikov Robin Kothari

Marcin Kotowski Michal Kotowski Jeremy Kroeker Alexandre Laplante Jonathan Lavoie Nicholas LeCompte Xian Ma Easwar Magesan Laura Mancinska Iman Marvian Michael Mazurek Thomas McConkey Evan Meyer-Scott Sergei Mikheev Hamid Mohebbi **Abel Molina Prieto** Felix Motzoi Takafumi Nakano Varun Narasimhachar Mohamad Niknam Joachim Nsofini Jean-Luc Orgiazzi Yingkai Ouyang Maris Ozols Adam Paetznick Daniel Park Gina Passante **Om Patange** David Pitkanen Chris Pugh Daniel Puzzuoli Farzad Qassemi Wenling Qiao Sadegh Raeisi Joseph Rebstock **Ansis Rosmanis Yuval Sanders Kurt Schreiter** Antonio Scotland Jamie Sikora Jamie Smith Gelo Noel Tabia **Denis-Alexandre Trottier** Cozmin Ududec Sarvagya Upadhyay Victor Veitch Zak Webb **Christopher Wood**

Rui Xian

Graduate Program

A message from the Quantum Information Graduate Program Director

Though many pioneering discoveries have already been made, the biggest impact IQC will have on the world will surely be through the achievements of the brilliant young researchers emerging from the institute. I'm grateful to my friend and IQC Board member Douglas Barber, whose reiteration of this point inspires us to provide the most comprehensive education and mentorship possible, and maintain ties with our alumni after they enter the workforce.

When we launched the collaborative quantum information graduate studies program in 2010, our goal was to provide the next generation of quantum pioneers with the resources and training they need to make their own discoveries in this fast-changing field.

Graduate students are a vital part of quantum information research at the University of Waterloo, whose fresh perspectives take the science in unexpected and important new directions.

Our immersive program has attracted some of the brightest young mathematicians, computer scientists, physicists, chemists and engineers from six continents. They benefit from an ever-growing array of courses presented in collaboration with the University of Waterloo's Faculties of Engineering, Mathematics and Science and they get hands-on training in IQC's state-of-the-art facilities.



The first group of students of this program are now completing their studies and entering exciting careers in academia, government, industry and beyond. They will be the first generation that takes quantum information science from fundamental research to real-world technologies that will benefit society. I can't wait to see what they'll accomplish.

In the coming pages, some of these brilliant young minds share what their experiences at IQC have meant to them.

Made M Michele Mosca, Deputy Director, IQC

Did you know that thanks to quantum information technology, atomic clocks are so precise that they won't lose or gain more than a second of the universe? second over the entire lifespan of the universe?

Meet our

Graduate Students



◀ Jonathan Lavoie

I feel lucky to have had the chance to play an active role in the formation and expansion of IQC's state-of-the-art quantum optics lab. Waterloo attracts

the best researchers in the field of quantum information and I am so happy to have found exactly what I was looking for, right here in Canada.



◀ Tomas Jochym-O'Connor

Being a part of IQC has provided great research potential within our scientific community while also providing the opportunity to share our findings with

the outside public through many different events such as workshops, visits and open houses.



◀ Elena Anisimova

IQC is a very unique place. It's one of the few centres dedicated to solving the problems of quantum computing and quantum information.

It is wonderful and exciting for me to find myself in such a community. There are so many talented and smart people around conducting research — it is really inspiring.



◀ Jeremy Kroeker

As a chemistry student, I have always been interested in the underlying mechanisms of how things work at the molecular level. The quantum

information graduate program seemed like a great opportunity to supplement my knowledge of chemistry with neat ways of exploiting quantum mechanics to process information at the molecular scale.



◀ Grant Cleary

IQC has always interested me in terms of research opportunities because of the critical mass of world-class talent gathered here. Regardless of the

specific field of scientific study, I find that there is always someone here who can either answer my questions, or at least point me in a few good directions to find what I am looking for. For me, having this breadth of expertise in such a tightly knit community has made it possible to move my research forward in ways that may not have been possible elsewhere.





Aimee Heinrichs

The quantum information-specific courses here at IQC have given me an excellent multidisciplinary background that has been advantageous in

collaborations and interactions abroad. I believe the connections and experiences I gain at IQC will definitely be assets in the future of my physics career.



◆ Christopher Granade

I have found that IQC is quite unique, not just in the depth of research opportunities available to me, but also in the variety. At IQC, I can take a class in the formalisms of

quantum error correction and back that up by taking classes that explore experimentally motivated noise models. I need not define myself as narrowly belonging to one sub-discipline, but can do all the research that interests me.



◀ Kent Fisher

IQC offers both a unique academic and cultural experience. Nowhere else would I even dream of being able to walk down a hall, find an expert on any topic in

quantum information, and ask them if they're playing ball hockey in the parking lot later.





◆ Daniel Park

IQC's unique quantum information graduate program offers a wide range of courses that cover almost all the topics in the field. I feel well prepared for my research through the

course work, and I enjoy auditing lectures on the topics that are not directly related to my research but teach me about other important aspects of quantum information science. Also there are a number of seminars at IQC every week where I learn about the recent research going on around the world — as well as in the labs next door.



◆ Om Patange

Being at IQC and working with Prof. David Cory has given me many unique and exciting opportunities. For example, I had the chance to build a confocal microscope from scratch, use my nanotechnology background to make samples

that will make a novel quantum processor, and mentor the next generation of nanotechnology engineering students.

Courses

FALL 2011

QIC 710 Quantum Information Processing

QIC 880 Nanoelectronics for Quantum Information Processing

QIC 820 Theory of Quantum Information

QIC 890 Design in Quantum Systems

WINTER 2012

QIC 750 Implementations of Quantum Information Processing

QIC 890 Optical and Atomic Implementations

QIC 890 Quantum Error Correction and Fault Tolerance

QIC 890 Applied Quantum Cryptography

SPRING 2012

QIC 891 Sir Anthony Leggett Lecture Series

QIC 890/891 Selected Advanced Topics in Quantum Information

IQC Alumni



◆ David Poulin

Photo credit: QuantumWorks

After earning his PhD at the Institute for Quantum Computing in 2004 and

working as postdoctoral fellow at Caltech, David joined the physics department at the University of Sherbrooke in 2008, earning tenure in 2011. During his PhD studies under IQC Executive Director Raymond Laflamme, he earned the W.B. Pearson Medal for the originality of his thesis, and the Alumni Gold Medal (awarded to the top graduate student at the University of Waterloo). His research is focused on quantum error correction, including the theory of operator codes and the creation of efficient decoding algorithms. One of his breakthroughs (published in *Nature*) was the discovery of a quantum Metropolis algorithm for a decade-old problem.



Marcus P. da Silva

Marcus earned his Master's and PhD from the University of Waterloo in Physics, having worked with IQC faculty

members Raymond Laflamme and Frank Wilhelm during his doctoral studies. He pursued a postdoctoral fellowship at the University of Sherbrooke, working in the Physics of Quantum Information (EPIQ) group, collaborating with fellow IQC alumnus David Poulin. His main area of research focus was the theory of practical characterization of states and processes in quantum experiments. In early 2011, he joined the Quantum Information Processing Group at Raytheon BBN Technologies in Cambridge, MA, where he has worked on projects ranging from quantum computing applications to quantum sensing and communications.



◀ Elham Kashefi

Elham was a postdoctoral fellow at the Institute for Quantum Computing from 2005 to 2006, after earning her PhD at

Imperial College London. She has explored the potential of quantum information theory, from its formal and foundational aspects to actual cryptographic experiments. She is now an associate professor at the University of Edinburgh School of Informatics. She was recently elected as an Associate Lecturer at the CNRS-Telecom ParisTech in 2011, and she co-founded QUISCO (Quantum Information Scotland network) in 2008. She co-developed a new cryptographic protocol (with IQC postdoctoral fellow Anne Broadbent) for universal blind quantum computing, which is considered a significant breakthrough in the field.

Awards &

Four IQC faculty earn Early Researcher Awards

Professors JONATHAN BAUGH, ANDREW CHILDS, THOMAS JENNEWEIN and ADRIAN LUPAŞCU were among the 21 University of Waterloo faculty members to receive the prestigious "Early Researcher Award" from the Ministry of Economic Development and Innovation. Early Researcher Awards grant up to \$100,000, to be matched by \$50,000 from the researcher's institution over a period of up to five years.



IQC Executive Director named as Fellow of APS and AAAS

For his pioneering contributions to quantum information science, IQC Executive Director RAYMOND LAFLAMME earned fellowships in two of the world's preeminent scientific organizations — the American Physical Society (APS) and the American Association for the Advancement of Science (AAAS). The APS selection committee recognized Laflamme "for his visionary leadership in the field of quantum information science, and for his numerous fundamental contributions to the theoretical foundations and practical implementation of quantum information processing, especially quantum error correction and linear optical quantum computing." At the 2012 AAAS General Meeting NSERC President Suzanne Fortier called Laflamme and the other AAAS Fellows "true champions for the advancement of science."





IQC postdocs earn prestigious fellowship

Congratulations to IQC postdoctoral fellows BRENDON HIGGINS (above, left) and EDUARDO MARTIN-MARTINEZ (right), who have earned the prestigious Banting Postdoctoral Fellowship, each valued at \$70,000 per year over two years. Higgins, who received the award in 2011, works on experimental approaches to quantum cryptography. Martin-Martinez earned the fellowship in 2012 to support his work in relativistic quantum information theory and quantum optics.

Recognition



CREATE Grants

Professors **DAVID CORY** and **MICHELE MOSCA** received prestigious federal grants worth \$1.65 million each to launch cutting-edge training and mentorship programs for young Canadian scientists. The Collaborative Research and Training Experience (CREATE) grants support the training of exceptional students and postdoctoral fellows by encouraging and improving collaboration, and gaining professional skills and relevant experience while addressing important scientific challenges. NSERC funds these grants.

Pictured: Minister of State (Science and Technology)

GARY GOODYEAR (centre) talks with recipients MICHELE MOSCA
(left) and DAVID CORY.

FACULTY AWARDS

RICHARD CLEVE

Distinguished Scientist at the Centrum Wiskunde & Informatica (2011)

RAYMOND LAFLAMME

Doctor Honoris Causa, The University of Sherbrooke (2012)

American Association for the Advancement of Science, Fellow (2012)

Fellow of the American Physical Society (2011)

MICHELE MOSCA

University Research Chair (2012)

POSTDOCTORAL FELLOWS

ANNE BROADBENT

CIFAR Junior Fellow (August 2011)

OLEG GITTSOVICH

Erwin Schrödinger Fellowship (July 2012)

BRENDON HIGGINS

Banting Postdoctoral Fellowship (April 2011)

EDUARDO MARTIN-MARTINEZ

Banting Postdoctoral Fellowship (April 2012)

AIDAN ROY

University of Waterloo Fields Scholarship (August 2010)

KRISTER SHALM

CIFAR Junior Fellow (October 2010)

STUDENT AWARDS

BELL FAMILY FUND FOR QUANTUM

Chris Erven
Chris Ferrie
Peter Groszkowski
Sarvagya Upadhyay
Robin Kothari
Jonathan Lavoie
Pierre-Luc
Dallaire-Demers
Evan Mever-Scott

DAVID R. CHERITOR GRADUATE

Jean-Luc Orgiazzi

SCHOLARSHIP Sevag Gharibian Sarvagya Upadhyay Abel Molina Prieto Matthew Amy Robin Kothari Ansis Rosmanis Stacey Jeffery

IQC ACHIEVEMENT

Felix Motzoi Farzad Qassemi Sarvagya Upadhyay Evan Meyer-Scott Maris Ozols Easwar Magesan Sevag Gharibian

IQC DAVID JOHNSTON AWARD FOR SCIENTIFIC

Chris Erven Jean-Luc Orgiazzi Gina Passante

IQC ENTRANCE

Kent Fisher Luke Govia Tomas Jochym-O'Connor Nickolay Gigov Christopher Wood Matthew Graydon Holger Haas Chris Pugh Denis-Alexandre Trottier

MIKE AND OPHELIA LAZARIDIS

Yingkai Ouyang Farzad Qassemi Iman Marvian Amin Eftekharian Ansis Rosmanis Abel Molina Prieto Sarvagya Upadhyay Juan Miguel Arrazola Joshua Geller Adam Paetznick Antonio Scotland

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATI SCHOLARSHIP — DOCTORAL

Easwar Magesan Jonathan Lavoie Sevag Gharibian Farzad Qassemi Matthew Graydon Stacey Jeffery Evan Meyer-Scott

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP —

MASTERS
Cozmin Ududec
Chris Ferrie
Easwar Magesan
Gina Passante
Deny Hamel
Daniel Criger
Pierre-Luc
Dallaire-Demers

Robin Kothari Evan Meyer-Scott Stacey Jeffery Kent Fisher Luke Govia Tomas Jochym-O'Connor Nickolay Gigov Chris Pugh Joseph Rebstock

Jamie Smith

NSERC POSTGRADUATE SCHOLARSHIP — DOCTORAL

Chris Erven Chris Ferrie Jamie Sikora Jamie Smith Felix Motzoi Robin Kothari

POSTGRADUATE SCHOLARSHIP — MASTER'S EXTENSION Cozmin Ududec Gina Passante Jamie Smith

Deny Hamel

Kent Fisher

NSERC VANIER
CANADA GRADUATE
SCHOLARSHIP
Gina Passante
Deny Hamel

ONTARIO GRADUAT

Jamie Sikora
Hamid Mohebbi
Cozmin Ududec
Kurt Schreiter
Thomas McConkey
Nathan Killoran
Fatin Haque
Evan Meyer-Scott
Jean Philippe
Bourgoin
Kent Fisher
Luke Govia

Victor Veitch

ONTARIO GRADUATI
SCHOLARSHIP
IN SCIENCE AND
TECHNOLOGY
Sevag Gharibian
Jamie Sikora
Felix Motzoi
Chunqing Deng
Peter Groszkowski
Thomas McConkey
David Pitkanen

ONTARIO TRILLIUM SCHOLARSHIP Zak Webb

PRESIDENT'S GRADUATE SCHOLARSHIP

Jamie Sikora
Cozmin Ududec
Chris Ferrie
Easwar Magesan
Gina Passante
Jamie Smith
Chris Erven
Hamid Mohebbi
Deny Hamel
Kurt Schreiter
Daniel Criger
Pierre-Luc

Dallaire-Demers
Robin Kothari
Jonathan Lavoie
Thomas McConkey
Evan Meyer-Scott
Sevag Gharibian
Stacey Jeffery
Nathan Killoran
Felix Motzoi
Farzad Qassemi
Kent Fisher
Luke Govia
Fatin Haque
Tomas JochymO'Connor

Jean Philippe Bourgoin Nickolay Gigov Matthew Graydon Chris Pugh Joseph Rebstock Victor Veitch

QUEEN ELIZABETH
II GRADUATE
SCHOLARSHIP
IN SCIENCE AND
TECHNOLOGY
Agnes Ferenczi
Alexandre Laplante
Yuval Sanders II



IQC to the World; the World to IQC

Scientific Outreach

Great science cannot happen in isolation. It must be shared with the people who support it, are fascinated by it, and will ultimately benefit from it. This has been a fundamental tenet of IQC since its inception a decade ago; today, the institute's outreach agenda is broader and more exciting than ever. As the research at IQC accelerates and achieves exciting new milestones, so too do the outreach activities aimed at sharing and explaining the research.

IQC's outreach efforts are tailored for each of the institute's target audiences, from prospective students and faculty to the general public and partners from government, academia and industry. Outreach activities — graduate fairs, public lectures, conferences, cultural collaborations, high school visits, publications, social media and many more — aim to educate, excite and inspire people about the quantum information revolution.

People are taking the quantum leap with IQC. Enrollment in IQC programs, camps and workshops is skyrocketing. A number of outreach efforts were launched in the past year — from scientific conferences to a quantum-themed symphony concert — with many more coming in the near future.

The following pages offer a snapshot of IQC's recent outreach efforts, and a glimpse at the exciting times ahead.







The IQC David Johnston Award for Scientific Outreach

Congratulations to the winners of IQC's Scientific Outreach Award

Up to three awards valued at \$2,500 are given annually to current graduate students at IQC who have shown an outstanding commitment to scientific outreach and community engagement. This award was created to celebrate Canadian Governor General David Johnston's vital contributions to IQC, his passion for leadership and his enthusiasm for continuous learning, innovation and achievement. David Johnston was president of the University of Waterloo from 1999 to 2010. The award is funded by Industry Canada.

This year's recipients (above, left to right): FARZAD QASSEMI, JAMIE SIKORA and EVAN MEYER-SCOTT.

Conferences, Workshops & Schools

General Quantumness of Correlations Mini-Workshop

February 23-24, 2012

Participants of this mini-workshop examined questions of non-classical correlations — including, but not limited to, quantum entanglement. Roughly 20 participants discussed what it means for a correlation to be quantum, and how such correlations can be tested, quantified and utilized in information processing.

Recent Progress in Quantum Algorithms

April 11-13, 2012

Two-dozen experts in quantum algorithms convened in Waterloo to discuss key questions and breakthroughs in the field. The conference, hosted jointly by IQC and the Perimeter Institute, featured formal talks, presentations and informal discussion periods aimed at forging new connections and sparking new ideas for investigation.

Undergraduate School on Experimental Quantum Information Processing (USEQIP)

May 28 - June 8, 2012

This annual program was designed to provide exceptional undergraduate students with hands-on experience in the field of quantum information processing. This year, 18 students from around the globe came to Waterloo to participate in the two-week camp and engage in experimental activities and theoretical lectures at IQC.

12th Annual Canadian Summer School on Quantum Information

June 11-16, 2012

This 12th edition of the annual event brought together students from around the world to learn about quantum information processing. The summer school gathered some of the world's top experts to offer lectures on various aspects of quantum information, and was geared toward students and postdoctoral fellows in computer science, mathematics and physics.

The 9th Canadian Student Conference on Quantum Information, and the 2nd AQuA Student Congress on Quantum Information and Computation

June 18-22, 2012

The event offered graduate students in the field of quantum information science an opportunity to come together and showcase their work with other students.



Quantum Cryptography School for Young Students (QCSYS)

August 13-17, 2012

An introductory workshop on key concepts in quantum cryptography aimed at high school students aspiring to study quantum science at university. This year, the summer school hosted 42 students from around the world.

√ Students visiting IQC for the Undergraduate School on Experimental Quantum Information Processing take a tour of the fabrication facility in RACI







Events

TEDxUW



In a captivating and inspirational talk, IQC postdoctoral fellow Krister Shalm described

the three personal discoveries that forever changed his life: poetry, physics and dance. On November 12 Shalm explained how his seemingly disparate passions — whether wrangling photons in an IQC lab or lindy-hopping to Dixieland jazz — form the poetry of his life.

Quantum Frontiers Distinguished Lecture Series

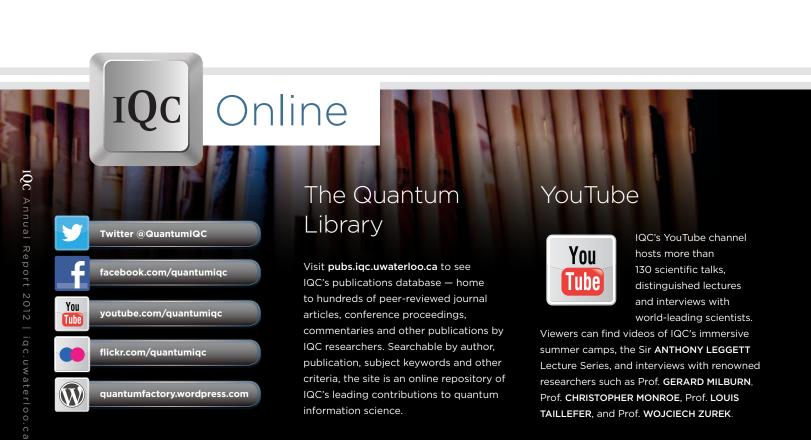
The lectures, presented once per term, explore the ways researchers are harnessing quantum mechanics to advance various fields at the forefront of science. IQC welcomed **DAVID WINELAND** (National Institute of Standards and Technology) in January, **LOUIS TAILLEFER** (University of Sherbrooke) in February, and **CHIP ELLIOTT** (GENI) in June.

▲ TEDxWaterloo

Postdoctoral Fellow Krister Shalm took to the stage at TEDxWaterloo March 21 as the ringleader of a boisterous extravaganza that included a live band, an illusionist, several-thousand M&Ms, hundreds of dancers and, of course, quantum physics.

Pictured above:

KRISTER SHALM used swing dance, live music and magic to explain quantum science at TEDxWaterloo.







Quantum: Music at the Frontier of Science

A pair of sold-out concerts by the Kitchener-Waterloo Symphony, created in collaboration with IQC, explored the parallel histories of music and quantum science over the past century. The concert, held on February 23 and 24, used narration, visuals, sound experiments and an eclectic musical program to carry the audience on a journey into the quantum realm.

Pictured above:

EDWIN OUTWATER conducts the Kitchener-Waterloo Symphony in "Quantum: Music at the Frontier of Science"

▲ Girls in Science

Approximately 15 elementary and high-schoolage girls from the Canadian Association for Girls in Science gathered at IQC for an afternoon of scientific discovery and fun. The girls learned the basics of cryptography through activities and games, such as decoding secret messages from *The Hunger Games* and *Harry Potter*, and they explored principles of optics with lasers and fibre-optic cables. The event aimed to give young girls fun experiences in typically male-dominated fields of science.

Pictured above:

IQC students RAZIEH ANNABESTANI and ELENA ANISIMOVA demonstrate polarization of light at the Girls in Science event held April 22





iqc.uwaterloo.ca

The IQC website is home to all of the information and resources relevant to the institute's target audiences — from prospective students and faculty to government and the general public. The site is a news source, recruiting tool, learning resource and a gateway to IQC social media.

The Quantum Factory

Visit quantumfactory.wordpress.com for news, videos, commentary and miscellaneous oddities from the amazing (and often amusing) world of quantum science.



Did you know that quantum computing could have applications in the design and discovery of new medicines in the future?

IQC's Global Reach

DURING THE 2011
CALENDAR YEAR,
IQC RESEARCHERS
COLLABORATED WITH:

126
external researchers
leading to the publication
of 50 joint papers

69
institutes from 20 countries

Quantum information science is multidisciplinary, bringing together researchers from many areas of expertise. IQC scientists consider collaboration a catalyst for discovery. Researchers at the institute often work closely with peers from organizations around the globe to publish and present results. The institute's international network is expanding, and these connections are laying the groundwork for exciting developments in the future.



National & International Agreements

IQC has signed eight official agreements to promote collaborative research with other organizations:

IBM

Indian Institute of Technology, Kanpur National Institute of Informatics, Japan National Research Council, Canada National Science Council of Taiwan National University of Singapore Raman Research Institute, India Tsinghua University, China

Annual Meeting of the American Association for the Advancement of Science (AAAS)

IQC had a strong presence at the AAAS Annual Meeting in Vancouver, February 2012. The meeting is the world's largest scientific gathering, with an estimated 12,500 participants this year, ranging from scientists and journalists to policy-makers and the general public. IQC faculty members including RAYMOND LAFLAMME, DAVID CORY and THOMAS JENNEWEIN participated in panel discussions with international colleagues, and the institute's outreach team developed international connections at the IQC booth.

MIKE LAZARIDIS delivered an inspirational plenary speech to an audience of thousands about why he supports cutting-edge science.



Mohamed Abutaleb, Massachusetts Institute of Technology Gerardo Adesso, The University of Nottingham Jason Alicea, University of California, Irvine

Itai Arad, The Hebrew University of Jerusalem

Vikram Sharad Athalye, Cummins College of Engineering for Women

Michal Bajcsy, Stanford University

Jacob Biamonte, University of Oxford

Howard Barnum Los Alamos National Laboratory Patrice Bertet, Commissariat à l'Energie Atomique, Saclay

Lev Bishop, University of Maryland Fernando Brandão, Belo Horizonte, Brazil Daniel Braun, University Toulouse Paul Sabatier

Misha Brodsky, AT&T

Aharon Brodutch, Macquarie University

Raffi Budakian, University of Illinois at Urbana-Champaign

Irfan Bulu Harvard University

Jonas Bylander, Massachusetts Institute of Technology

John Calsamiglia, Universitat Autònoma de Barcelona

Paola Cappellaro, Massachusetts Institute of Technology

Carlton M. Caves, University of New Mexico

Marcos Cesar de Oliveira, Universidade Estadual de Campinas

Donny Cheung, Tornado Medical Systems Eric Chitambar, University of Toronto

Matthias Christandl, Institute for Theoretical Physics Zürich

Roger Colbeck, Perimeter Institute

Antonio Corcoles, IBM

Jason Crann. Carleton University

Toby Cubitt, Universidad Complutense de Madrid

Hang Dinh, Indiana University South Bend Helen Fav Dowker, Imperial College London Luming Duan, University of Michigan

Freeman Dyson, Institute for Advanced Study,

Princeton University

Dirk R England Columbia University

Jay Erker, University of California, Davis

Omar Fawzi. McGill University

Steve Flammia, University of Washington

 $\textbf{Chi-Hang Fred Fung}, \ \textbf{The University of Hong Kong}$

Joshua Geller, University of Rochester Alexev Gorshkov, Harvard University

Fabio Grazioso, École Normale Supérieure Cachan

Adam Green, University of Calgary

Simon Gröblacher, California Institute of Technology

Jeongwan Haah, California Institute of Technology

Alioscia Hamma, Perimeter Institute

Lucien Hardy, Perimeter Institute

Aram Harrow, University of Washington Andrew Houck, Princeton University

Peter Høver. University of Calgary

Hannes Hübel, Stockholm University

Kazuo Iwama. Kvoto University

Rahul Jain, Centre for Quantum Technologies,

National University of Singapore

Liang Jiang, Caltech

Stephen P. Jordan. National Institute of Standards and Technology

María José García, Spanish National Research Council

Sarah Kaiser. Bethel University

David Kaiser, Massachusetts Institute of Technology

Dongpeng Kang, University of Toronto Marc Kaplan, University of Montreal

Gurneet Kaur, Massachusetts Institute of Technology

Yoon-Ho Kim, Pohang University of Science & Technology

Jens Koch, Northwestern University

Dax Enshan Koh, Stanford University

Vladimir Korepin, Stony Brook University

Yuimaru Kubo, French Alternative Energies and Atomic **Energy Commission**

Daniel Kumar, University of North Carolina at Chapel Hill

Mitsuru Kusumoto, Kyoto University

Paul G. Kwiat, University of Illinois at Urbana-Champaign

Thomas Lauprêtre, Laboratoire Aimé Cotton

Jonathan Leach, University of Ottawa Thomas Lehner, Dotfast-Consulting

Marko Loncar, Harvard School of Engineering and Applied Sciences

Dawei Lu, University of Science and Technology of China Shunlong Luo, Academy of Mathematics and Systems

Science Chinese Academy of Sciences

Thomas Lutz. Universität Ulm

Vadim Lyubashevsky, École Normale Supérieure. Paris

Steve MacLean, Canadian Space Agency Frédéric Magniez, Université Paris Diderot

Loïck Magnin, Centre for Quantum Technologies, National

University of Singapore

Arka Maiumdar. Stanford University

Matteo Mariantoni, University of California, Santa Barbara

Igor Markov. University of Michigan

Eduardo Martin-Martinez, Instituto de Fisica Fundamental

Ralph Merkle, Singularity University

Maiken Mikkelsen. University of California. Berkeley Nathaniel Nelson-Fitzpatrick, University of Alberta

Leonardo Neves, University of Concepción, Center for Optics and Photonics

Corev O'Meara, University of Guelph

Steven Olmschenk, University of Maryland

Gerardo Ortiz, Indiana University Bloomington

Hanhee Paik, Yale University

Mauro Paternostro, Queen's University

Jason Petta. Princeton University

Daniel Posch, Office of Science and Technology

Benedikt Pressl, Universität Innsbruck

Robert Prevedel. Research Institute for Molecular Pathology and Max E Perutz Laboratories GmbH

Timothy Ralph, University of Queensland

Chandrasekhar Ramanathan, Dartmouth College

Christopher Raub, University of California, Irvine

Grégoire Ribordy, id Quantique

David Rideout, University of California, San Diego

Arnau Riera, Potsdam University

Alexander Rimberg, Dartmouth College

Terence G. Rudolph, Imperial College London

Mary Beth Ruskai. Tufts University

Vincent Russo, Wayne State University

Kei Sano, Kyoto University

Dylan Saunders, Griffith University

Carmelo Scarcella, Politecnico Di Milano

Leonard Schulman, California Institute of Technology

Naresh Sharma. Tata Institute of Fundamental Research

Fred Shultz, Wellesley College

Irfan Siddigi. University of California, Berkeley

Ray Simmonds, National Institute of Standards and Technology

Jonathan Simon, Harvard University

Sidharth Somanathan, Texas A&M University

Rolando Somma, Los Alamos National Laboratory

William Stacey. University of Alberta David J. Starling, University of Rochester

Douglas Stebila, Queensland University of Technology

Gordon Stovel, Canadian Foundation for Innovation

Dieter Suter. Universität Dortmund

Mario Szegedy, Rutgers University

Louis Taillefer. University of Sherbrooke Yongchao Tang, Tsinghua University

Seiichiro Tani, Nippon Telegraph and Telephone

Communication Science Laboratories Daniel Terno. Macquarie University

Junichi Teruyama, Kyoto University

Academic & Scientific Visitors

Visitors from May 1, 2011 to April 30, 2012

Oleg Tretiakov, Texas A&M University

Sarvagya Upadhyay, Centre for Quantum Technologies.

National University of Singapore

Berkant Ustaoğlu, Sabanci University

Maarten van den Nest, Max Planck Institut für

Quantenoptik

Ramarathnam Venkatesan, Microsoft Research

Rajamani Vijayaraghayan, University of California, Berkeley

Paolo Villoresi, University of Padova

Amy Wang, Tsinghua University Yun-ijang Wang, University of Calgary

Tzu-Chieh Wei, University of British Columbia

Gregor Weihs, University of Innsbruck

Yaakov Weinstein, MITRE Corporation

Birgitta Whaley, University of California, Berkeley

Christopher Wilson, Chalmers University of Technology David Wineland, National Institute of Standards

and Technology

Jörg Wrachtrup, University of Stuttgart

Xiaodi Wu. University of Michigan

Lianao Wu, Universidad del País Vasco

Amir Yacoby, Harvard University Yutaro Yamaguchi, Kyoto University

Jun Yong Khoo, University of Oxford Beni Yoshida, Massachusetts Institute of Technology

Nengkun Yu, Tsinghua University and University

of Technology

Shizhong Zhang, Ohio State University

Shengyu Zhang, The Chinese University of Hong Kong Hongchao Zhou, California Institute of Technology

Leard

Did you know that electron bean lithography enables the creation of patterns as small as 20 nanometers in size? That's 20 billionths of a metre.

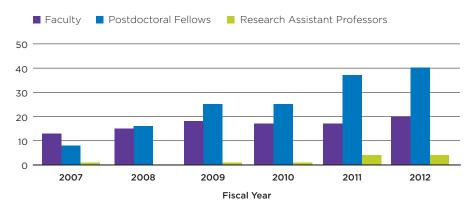
The Year in Review IQC by the Numbers

MAY 1, 2011 TO APRIL 30, 2012

Researchers at IQC

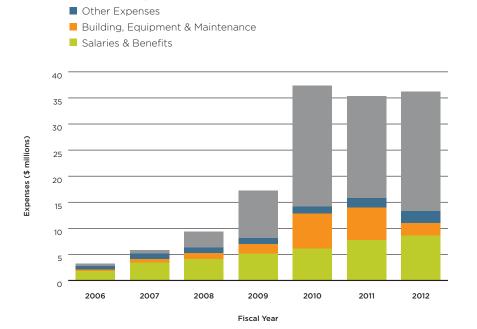
IQC is home to **20** faculty members, **4** research assistant professors, **40** postdoctoral fellows, **96** graduate students, **36** research assistants, **21** long-term visitors, **6** technical specialists and **20** communications, information technology and administrative staff.

Faculty & Postdoctoral Fellows



Annual Expenditures

QNC Building



LONG-TERM VISITORS

Vikram Sharad Athalye Amin Baumeler Aleksandrs Belovs Troy Borneman Guanru Feng Thomas Guenthner Bettina Heim Won-Young Hwang
Shelby Kimmel
Antti Karlsson
Yusuke Kondo
Christian Konrad
Kevin Krsulich
Jun Li

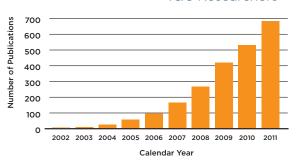
Thomas Lutz
Laura Piispanen
Carmelo Scarcella
Hou Shiyao
Sarah Sheldon
Virginia Villanueva
Yafei Yu

Publications

Notable publications in the journals *Nature Photonics*, *Nature Physics*, *Nature Communications*, *Physical Review Letters*, *Science*, *STOC*, *FOCS* and the Journal of Mathematical Physics represent high-level, peer-reviewed discoveries by IQC researchers.

Publication	2007	2008	2009	2010	2011
Nature	3	2	1	3	1
Nature Photonics			1	1	1
Nature Physics	1	1	5	5	3
Nature Communications					1
Physical Review Letters	10	7	16	14	17
Science	2	1	1	1	2
STOC	1	2	1	2	
FOCS			3		1
Journal of Mathematical Physics		1	2	2	4

Cumulative Publications by IQC Researchers



Cumulative Citations of IQC Publications: Google Scholar 15,000 5,000 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 Calendar Year

Governance

IQC Board of Directors

Tom Brzustowski (Chair), RBC Professor, Telfer School of Management Douglas Barber, Distinguished Professor-in-Residence, McMaster University

Paul Corkum, University of Ottawa and National Research Council

Robert Crow, Executive in Residence, IQC

George Dixon, Vice-president, University Research, University of Waterloo

Cosimo Fiorenza, Vice-president and General Counsel, Infinite Potential Group

David Fransen, Consul General, Canadian Consulate General in Los Angeles

Peter Hackett, Executive Professor, School of Business at the University of Alberta & Fellow, National Institute for Nanotechnology

Raymond Laflamme, Executive Director, IQC

Mike Lazaridis, Founder, Board Vice-Chair, and Chair of the Innovation Committee of Research In Motion Limited

Michele Mosca, Deputy Director, IQC

Peter Nicholson, Retired President, Council of Canadian Academies

William R. Pulleyblank, Professor of Operations Research, United States Military Academy, West Point

Executive Committee

George Dixon (Chair), Vice-president, University Research

Robert Crow, Executive in Residence, IQC
Ian Goulden, Dean, Faculty of Mathematics
Raymond Laflamme, Executive Director, IQC
Terry McMahon, Dean, Faculty of Science
Michele Mosca, Deputy Director, IQC

Pearl Sullivan, Dean, Faculty of Engineering, IQC

Scientific Advisory Committee

Prof. Gerard Milburn (Chair), University of Queensland

Prof. Harry Buhrman, Centrum voor Wiskunde en Informatica

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

Prof. Christopher Monroe, University of Maryland

Prof. Umesh Vazirani, University of California, Berkeley

Prof. Anton Zeilinger, University of Vienna

Prof. Wojciech Hubert Zurek, Los Alamos National Laboratory and Santa Fe Institute

Management & Administration

Management

Raymond Laflamme, Executive Director Robert Crow, Executive in Residence Michele Mosca, Deputy Director

Laboratory Support

Vito Logiudice, Director of Operations, Fabrication Facility

Brian Goddard, Senior Fabrication Equipment Technologist, Lab Instructor

Nathan Nelson-Fitzpatrick, Nanofabrication Process Engineer

Roberto Romero, Electronics and Instrumentation Technologist

Rodello Salandanan, Senior Equipment Technologist Ivar Taminiau, Laboratory Technician

Communications and Outreach

Jasmine Graham, Communications Officer
Jaymis Goertz, Web and e-Communications Officer

Craig Hennessey, Videographer

Colin Hunter, Senior Communications Officer

Peter Kovacs, Videographer

Martin Laforest, Manager, Scientific Outreach
Kimberly Simmermaker, Events, Outreach &
Communications Co-ordinator

Information Technology

Steve Weiss, Associate Director, Information Technology

Matthew Cooper, Client Support Specialist Ryan Goggin, Computing Specialist

Administration

Lorna Kropf, Assistant Director, Administration
Matt Schumacher, Associate Director, Finance
Andrew Dale, Administrative Co-ordinator/
Financial Assistant

Lisa David, Administrative Assistant

Monica Dey, Graduate Program Coordinator and Recruitment Assistant

Melissa Floyd, Administrative Support

Matthew Fries, Visitor Co-ordinator

Chin Lee, Assistant to the Deputy Director

Mary Lyn Payerl, Financial Administrator

Wendy Reibel, Administrative Officer

Carly Turnbull, Administrative Assistant

Thank you

IQC thanks Mike and Ophelia
Lazaridis, the Province of Ontario,
Industry Canada and Canada's
Economic Action Plan for their
visionary support.

Thank you to the following individuals and organizations for their generous and continued support of IQC:

Advanced Research and Development Activity

Army Research Office

Bell Family

Bruker Biospin Canada

Canada Excellence Research Chairs

Canada Foundation for Innovation

Canada Research Chairs

Canada's Economic Action Plan

Canadian Institute for Advanced Research

Canadian Institute for Photonic Innovations

COM DE\

Communications Security Establishment Canada

Defense Advanced Research Projects Agency

Disruptive Technology Office

Government of Canada

Government of Ontario

IBM

Industry Canada

Intelligence Advanced Research Projects Agency

Mathematics of Information Technology and Complex Systems

Mike and Ophelia Lazaridis

Natural Science and Engineering Research Council

Ontario Centres of Excellence

Ontario Innovation Trust

Ontario Research Fund

Perimeter Institute for Theoretical Physics

Premier's Research Excellence Fund

QuantumWorks

Research In Motion

The Ontario Ministry of Economic Development and Innovation

The University of Waterloo

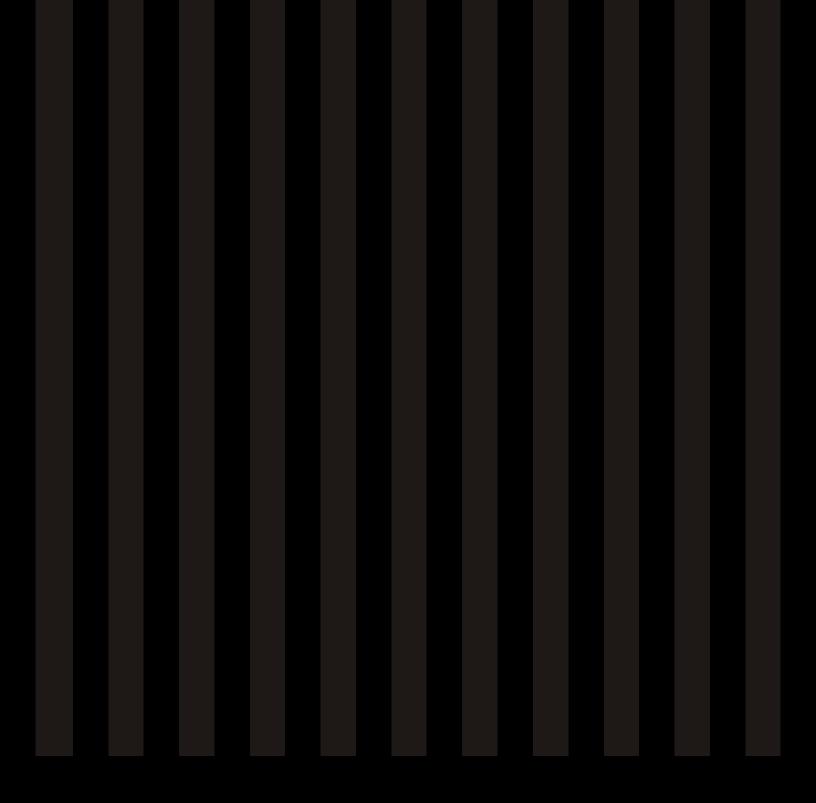
Special thanks to the University of Waterloo, IQC's home, for supporting and celebrating research, innovation and excellence.











Published by:

IQC Communications & Outreach

JASMINE GRAHAM **COLIN HUNTER**

iqc.uwaterloo.ca



