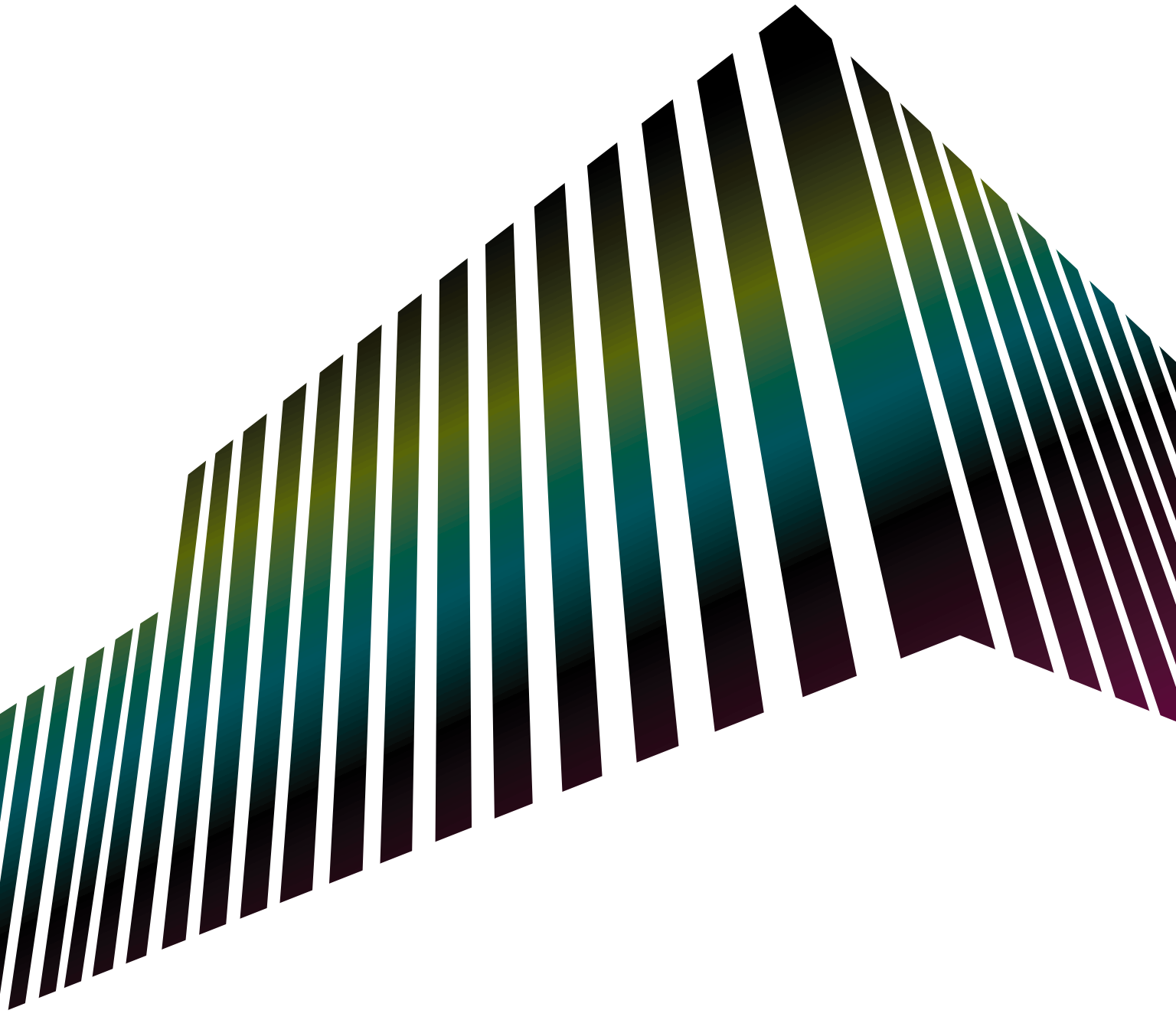


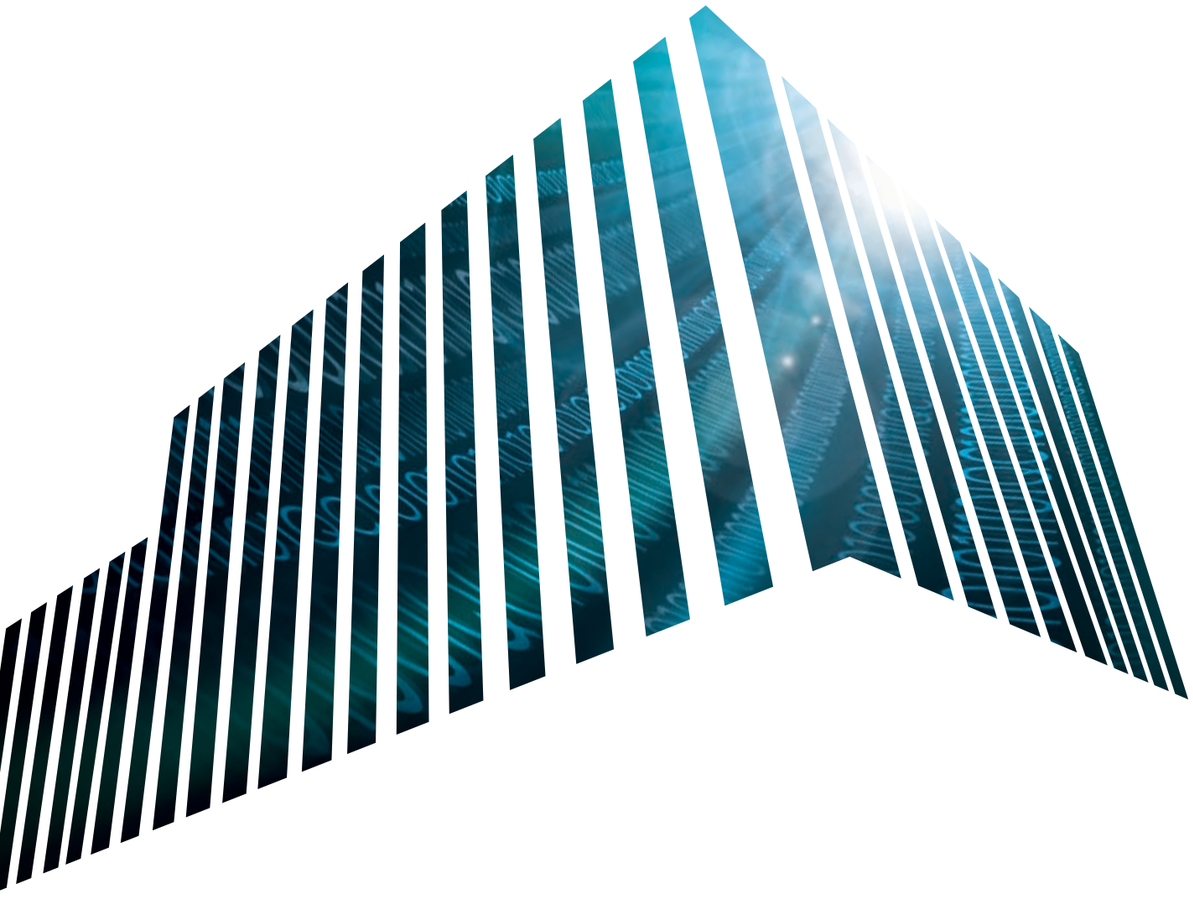
2015 ANNUAL REPORT

[LEADING THE NEXT QUANTUM REVOLUTION]

IQC Institute for Quantum Computing

“WHAT’S HAPPENING HERE IN WATERLOO IS TRULY SPECIAL, FROM THEORY TO EXPERIMENT AND BEYOND.”

PROFESSOR STEPHEN HAWKING



2015 ANNUAL REPORT

[LEADING THE NEXT QUANTUM REVOLUTION]

IQC Institute for Quantum Computing

PUBLISHED BY: IQC COMMUNICATIONS AND STRATEGIC INITIATIVES

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SHAPING CANADA'S QUANTUM FUTURE

[MESSAGE FROM THE EXECUTIVE DIRECTOR]

OVER THE LAST THIRTEEN YEARS, I HAVE PARTICIPATED IN AN EXPERIMENT – AN EXPERIMENT TO CREATE A NEW INDUSTRY FOR CANADA. WHEN IQC STARTED OUT IN A REMOTE CORNER OF THE UNIVERSITY OF WATERLOO, I ONLY IMAGINED A DYNAMIC COMMUNITY OF RESEARCHERS WORKING IN A WORLD-CLASS ECOSYSTEM. I NO LONGER HAVE TO IMAGINE THIS.

Our bold vision is now a reality. IQC is home to nearly 200 researchers. Our community of faculty, students and postdocs are producing mind-boggling results in an accelerated fashion placing IQC among the world leaders in quantum information research. And to my own surprise, IQC has spurred six startup companies in these short thirteen years. If you had asked me if we would have startup companies today back in 2002, I might have chuckled with nervous laughter. I would have never guessed the technologies would emerge this quickly. Yet, I am immensely proud that they have. That means our researchers are making incredible progress.

Going forward, IQC must continue to push the boundaries of our knowledge in quantum information. We have learned much, but there is much more to explore. We now understand the quantum world and how to harness its behaviours. The next great challenge will be to translate that knowledge into more relevant and diverse technologies. Our growing industry partnerships will be key in our success in this area. These partners will bring us questions and our job will be to use quantum technologies to solve these problems and turn those technologies into commercial opportunities.

This experiment is made possible by some incredible Canadian visionaries – Mike and Ophelia Lazaridis, Doug Fregin, the leadership of the University of Waterloo and both provincial and federal governments. With their ongoing support, I have no doubt that we will continue to succeed in this bold experiment. IQC will be an engine for Canada's future economy. We will grow the Quantum Valley with more research breakthroughs, more technologies, more companies, more investments and a tangible societal impact. In a challenging economic environment, I am immensely proud that our work is a shining beacon of future prosperity.

I look forward to the next year ahead and seeing how our continued experiment shapes the future for Canada.

Sincerely,

Raymond Laflamme
Executive Director
Institute for Quantum Computing
University of Waterloo

[MESSAGE FROM THE BOARD CHAIR]

As I think about the important work done by researchers at the Institute for Quantum Computing and the researchers at its theoretical counterpart, the Perimeter Institute for Theoretical Physics, and how their efforts have created the foundation for the establishment of the Quantum Valley in the Waterloo Region, I am reminded of Vannevar Bush's famous report to U.S. President Harry S. Truman in 1945 called "Science: the Endless Frontier". Bush spoke about the fundamental importance of basic research as a driver of improved health, prosperity, and security for society:

> *"New products, new industries, and more jobs require continuous additions to knowledge of the laws of nature, and the application of that knowledge to practical purposes. This essential, new knowledge can be obtained only through basic scientific research.... Without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world."*

Many of us believe that we are witnessing the beginning of a new global industry based on quantum technology that will transform society. As a result of the efforts made more than a decade ago to invest in quantum technology development in this Region, the Quantum Valley of Canada has the opportunity to be one of a handful of centres that will lead the world in this new industry.

I believe that we can draw a comparison to researchers at Bell Labs in New Jersey as well as researchers and graduates from California institutions including Stanford, Berkeley, Santa Cruz, San José State and others, that helped lay the foundations for the Silicon Valley in North California. Their work created technologies whose commercialization led to the early Silicon Valley companies such as Fairchild, Intel, Hewlett Packard, and Rockwell.

The Quantum Valley of Canada already has a number of new companies. These companies are well down the path toward the development and commercialization of transformative new technologies for global markets and we are optimistic that they, like Fairchild and the other early Silicon Valley companies, will lay the foundation for a global large scale quantum technology commercialization ecosystem in Canada.

I wish to acknowledge the University of Waterloo, the Government of Canada and the Province of Ontario who have been fundamental partners and investors in IQC since its inception as part of one of Canada's most successful public private partnerships. I also want to thank the members of the IQC Board of Directors and the IQC Scientific Advisory Committee for their efforts in support of IQC. In particular I want to acknowledge and thank Dr. Tom Brzustowski for his invaluable contribution as founding Chair of the IQC Board of Directors. Tom helped us to build the Board, to create its governance and to build its strong relationship with the rest of the University. We look forward to his continued support and advice as a valued Board member.

Today, just thirteen years after its founding at the University of Waterloo, IQC's researchers are recognized as leaders in their fields. The research infrastructure here is second to none. That said, there is still much work to do. IQC is at the half way point of its faculty complement. We must continue to attract the world's most talented researchers and students to Waterloo. We must continue to strive for global excellence and to compete with the very best institutions and laboratories for top talent. We also need to continue to foster spin off companies and shepherd technologies out into the global market.

Thirteen years ago, IQC was itself a nascent research group. Today, it sits among the top four research institutes in the world. IQC is enabling Canada to shape and participate in the next great technological revolution. And I believe IQC will continue to play a key and fundamental role for Canada, its citizens, its industry and prosperity.

Sincerely,

Mike Lazaridis
Chair, Board of Directors
Institute for Quantum Computing
University of Waterloo

BUILDING THE QUANTUM VALLEY

AN OVERVIEW OF IQC

THE DRIVE FOR EXCELLENCE AND INNOVATION

[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.

Quantum mechanics describes our universe at its most fundamental level. The building blocks of nature – atoms, molecules and photons – exhibit intriguing behaviours that are radically different than what we experience in our daily lives. The Institute for Quantum Computing (IQC) is harnessing the power of quantum, transforming the way we live, work and communicate through novel advances in fields spanning computing, communications, sensors and materials.

IQC was officially created in 2002, sparked by the vision of **MIKE LAZARIDIS**, to foster pioneering research into the next technological revolution – quantum information science. Today, IQC is a highly successful partnership between the University of Waterloo, the private sector and federal and provincial governments.

Building on the University of Waterloo's long-standing strengths in science, engineering, mathematics and computer science, IQC continues to recruit and train world-class quantum theorists and experimentalists from across the globe. IQC has developed an extensive and comprehensive multidisciplinary research program with a focus on quantum information science and technology, ranking among the top four research institutes worldwide. IQC's unique training opportunity for postdoctoral fellows and graduate students is internationally recognized for preparing tomorrow's leaders of the quantum revolution.

Now settled into the Mike & Ophelia Lazaridis Quantum-Nano Centre and continuing its expansion at the Research Advancement Centres I and II, IQC will accelerate the development of quantum technologies for applications from quantum computing to quantum sensors, from unbreakable cryptography to new quantum materials. Global collaboration, research advancements, commercialized applications and spinoff companies emerging from IQC are positioning Canada as a world leader in quantum information science and technology, building the "Quantum Valley" right here in Waterloo, Ontario, Canada.

> "THIS IS WHERE NEW, UNTOUCHED IDEAS ARE GENERATED."
>
> FERIDUN HAMDULLAHPUR,
> PRESIDENT, UNIVERSITY OF WATERLOO

[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]

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

THE BREADTH AND QUALITY OF IQC'S RESEARCH INFRASTRUCTURE AND COLLABORATIVE CULTURE ALLOWS QUANTUM INFORMATION SCIENCE AND TECHNOLOGY ADVANCEMENT AT THE HIGHEST INTERNATIONAL LEVEL. RESEARCHERS AT IQC COLLABORATE TO HARNESS THE QUANTUM WORLD, REVOLUTIONIZE TECHNOLOGY AND DRIVE FUTURE ECONOMIES. ULTRA-POWERFUL COMPUTERS, UNBREAKABLE CRYPTOGRAPHY, QUANTUM DEVICES, NEW MATERIALS AND NANOTECHNOLOGIES OF UNPRECEDENTED EFFICIENCIES ARE SOME OF THE DISCOVERIES BEING PIONEERED AT IQC. THE NEXT QUANTUM REVOLUTION IS HERE.

WORLD-CLASS SCIENCE, WORLD-CLASS PEOPLE

LEADING THE NEXT QUANTUM REVOLUTION

[CORE AREAS OF RESEARCH]

Quantum Information Theory

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

Quantum Algorithms

Developing instructions for quantum information processors to 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 noise.

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

Using engineered 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.

[ATTRACTING WORLD-CLASS PEOPLE]

RAFFI BUDAKIAN

RAFFI BUDAKIAN joined IQC in July 2014 as the Nanotechnology (WIN) Endowed Chair in Superconductivity in Waterloo's physics and astronomy department. He was a visiting scientist at the IBM Almaden Research Centre after earning his bachelor's, master's and PhD degrees from the University of California, Los Angeles.

The World Technology Network awarded him the World Technology Award in 2005 for his work in the detection of single electron spins. That same year, Budakian joined the University of Illinois at Urbana-Champaign.

At IQC, Budakian continues his research in the use of spins, one of the most promising approaches being applied to quantum information processing.

MICHAEL REIMER

University of Waterloo alumnus **MICHAEL REIMER** returned to Canada in February as an Assistant Professor in the Department of Electrical and Computer Engineering. Reimer completed his Master of Science degree in Engineering Physics from the Technical University of Munich, Germany, and went on to earn his PhD in Physics from the University of Ottawa/National Research Council of Canada.

Most recently, he was a postdoctoral researcher at the Technical University of Delft in the quantum optics lab of Professor Val Zwiller where he developed solid-state quantum devices. During this time, he made a significant impact in the development of single photon and entangled photon sources based on shaped nanowire heterostructures, as well as nanowire-based single electron devices and efficient nanowire avalanche photodiodes. In 2013 he was involved with Single Quantum, a startup company developing highly efficient single-photon detectors based on superconducting nanowires.

Reimer's research at IQC focuses on the development of quantum photonic devices and optical approaches needed to advance quantum information science and technologies, as well as to test fundamental questions in quantum photonics.

EDUARDO MARTÍN-MARTÍNEZ

Recipient of the John Charles Polanyi Prize for Physics in 2014, **EDUARDO MARTÍN-MARTÍNEZ** came to IQC as Research Assistant Professor in October 2014. Martín-Martínez completed his PhD in Theoretical Physics at the Universidad Complutense de Madrid, Spain. He was a postdoctoral researcher at IQC and the Perimeter Institute of Theoretical Physics.

Martín-Martínez's research in relativistic quantum information (RQI), a new and increasingly active research field, combines general relativity with quantum information theory. He brings relativistic approaches to quantum information research and uses quantum theories to explore relativity and the structure of space-time.

[FACULTY]

Research at IQC is fundamentally interdisciplinary, spanning theory and experiment to pursue every avenue of quantum information science. IQC fosters collaborations across the sciences and across borders. Our researchers are appointed to both IQC and one of seven departments across three faculties at the University of Waterloo: Combinatorics and Optimization, Applied Mathematics, Pure Mathematics or Computer Science in the Faculty of Mathematics; Physics and Astronomy or Chemistry in the Faculty of Science; and Electrical and Computer Engineering in the Faculty of Engineering.

FACULTY

Michal Bajcsy
Electrical and Computer Engineering
IQC member since
2014

Jonathan Baugh
Chemistry
IQC member since
2007

Raffi Budakian
Physics and Astronomy
IQC member since
2014

Andrew Childs
Combinatorics and Optimization
IQC member since
2007

Kyung Soo Choi
Physics and Astronomy
IQC member since
2014

Richard Cleve
School of Computer Science
IQC member since
2004

David Cory
Chemistry
IQC member since
2010

Joseph Emerson
Applied Mathematics
IQC member since
2005

Thomas Jennewein
Physics and Astronomy
IQC member since
2009

Raymond Laflamme
Executive Director
Physics and Astronomy
IQC member since
2002

Debbie Leung
Combinatorics and Optimization
IQC member since
2005

Adrian Lupascu
Physics and Astronomy
IQC member since
2009

Norbert Lütkenhaus
Physics and Astronomy
IQC member since
2006

Matteo Mariantoni
Physics and Astronomy
IQC member since
2012

Guo-Xing Miao
Electrical and Computer Engineering
IQC member since
2011

Michele Mosca
Co-founder
Combinatorics and Optimization
IQC member since
2002

Ashwin Nayak
Quantum Information Graduate Program Director
Combinatorics and Optimization
IQC member since
2002

Vern Paulsen
Pure Mathematics
IQC member since
2015

Michael Reimer
Electrical and Computer Engineering
IQC member since
2015

Kevin Resch
Physics and Astronomy
IQC member since
2006

John Watrous
School of Computer Science
IQC member since
2006

Christopher Wilson
Electrical and Computer Engineering
IQC member since
2012

RESEARCH ASSISTANT PROFESSORS

Vadim Makarov
Physics and Astronomy
IQC member since
2012

Eduardo Martín-Martínez
Applied Mathematics
IQC member since
2014

Dmitry Pushin
Physics and Astronomy
IQC member since
2010

William Slofstra
IQC
IQC member since
2015

FROM THE LARGEST PARTS OF THE UNIVERSE TO THE SMALLEST QUANTA OF PARTICLES, MATHEMATICS DESCRIBES AND HELPS US UNDERSTAND THE WORLD AROUND US. INTRIGUED BY THE CHALLENGE OF INVESTIGATING THE MATHEMATICS OF QUANTUM INFORMATION, PROFESSOR **JOHN WATROUS** EXPLORES QUANTUM INFORMATION THEORY, QUANTUM COMPLEXITY THEORY AND QUANTUM ALGORITHMS.

THE MATHEMATICS OF QUANTUM INFORMATION

It was Peter Shor's breakthrough in 1994 – the quantum factoring algorithm – that first attracted Watrous to quantum information theory. At the time he was studying classical computational number theory, but found Shor's algorithm so fascinating that he has been studying quantum information theory ever since.

In a recent collaboration with former Research Assistant Professor **MARCO PIANI** (now Lecturer at the University of Strathclyde), Watrous analyzed the impact of quantum steering – a feature of quantum mechanics related to entanglement through which a measurement performed on a particle can affect another distant particle. Considering a theoretical physical process, such as sending a message between two parties, performing a quantum computation, or measuring a system, Watrous and Piani found that the steering effect provides an advantage in learning what has happened in these types of tasks. They developed a mathematical method for precisely quantifying the impact of quantum steering and relating it to the task of distinguishing physical processes.

[UNEXPECTED RESEARCH CONNECTIONS]

These findings could be useful in fields such as quantum metrology and quantum cryptography where secret keys are created between two parties to encrypt messages for private communication. However, Watrous emphasizes that it is not yet clear where there might be other potential applications. Fundamental questions in quantum information theory are often found as underlying common threads tying together different areas of research. As ideas developed for one particular problem are applied to another, unexpected research connections are made and the results can be surprisingly useful in other areas.

[BUILDING THE FIELD OF QUANTUM RESEARCH]

Not long after the introduction of Shor's algorithm, it was predicted that the first quantum computer would take several decades to develop. Researchers are still working towards the realization of a practical quantum computer more than 20 years later, but are making steady progress. The power of quantum computing over classical computing is proven in many cases; yet there are still many unanswered theoretical questions. Watrous hopes to continue contributing to the progress in this field. His upcoming book on the theory of quantum information is one way he is doing just that. Evolved from course notes developed for a class Watrous taught on the same subject, the first draft of the book is under review with plans to be published in the future.

WEB

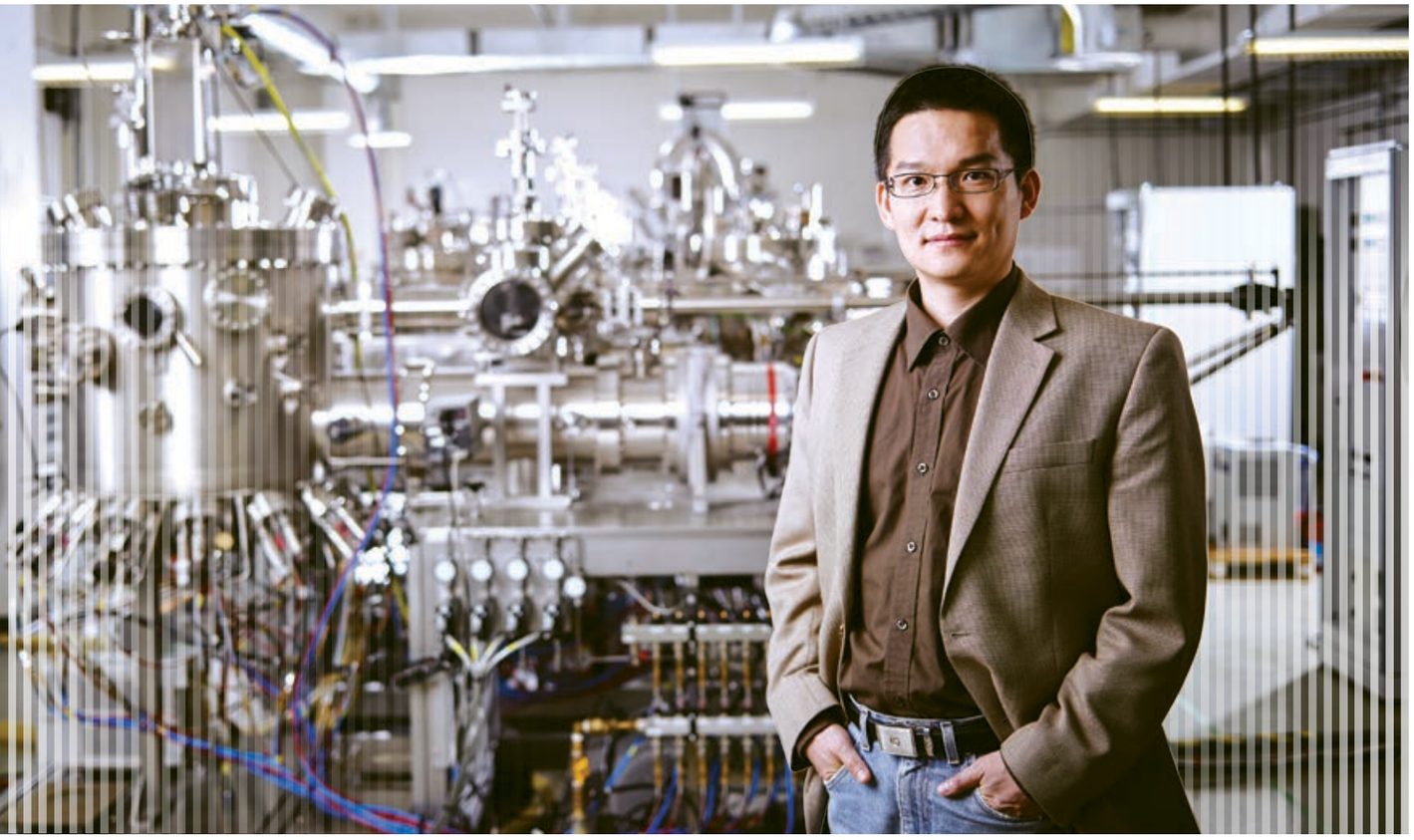
Necessary and Sufficient Quantum Information Characterization of Einstein-Podolsky-Rosen Steering:
http://bit.ly/quantum-steering

PLAYING A QUANTUM GAME

In his spare time, PhD student **DANIEL PUZZUOLI** enjoys rock climbing. Finding the most efficient way to climb to the top using the right positioning and movement requires on-the-spot problem solving – similar to the all-or-nothing approach to problem solving in Puzzuoli's research.

His most recent work is on a discrimination game problem. In this theoretical game, two known quantum processes can happen. Which process actually takes place is unknown. The game part, as Puzzuoli explains, is to determine which process occurs given that it only runs once on an input of your choosing. Since the process is quantum mechanical, using an input that is entangled to some other system can provide an advantage in the game. The goal of his research is to find pairs of processes for which the optimal performance in the game is limited by how much a single system can be entangled with multiple other systems.

While Puzzuoli's research focuses mainly on the mathematics of quantum information, he values the opportunity to learn about other research areas that fall under the umbrella of quantum information. He discusses ideas with supervisor **JOHN WATROUS** and finds the collaborative environment at IQC helpful. He often attends presentations that are outside of his field. "You never know when an idea might pop up that relates to something you're working on."



THE ADVANCEMENT OF CLASSICAL ELECTRONICS IS PREDICTED TO REACH ITS LIMIT WITHIN THE NEXT TWO DECADES. OVERALL COMPUTER-PROCESSING POWER AND THE NUMBER OF TRANSISTORS PER COMPUTER CHIP CONTINUES TO INCREASE, AS PROJECTED BY MOORE'S LAW. SOON ENOUGH, THE TRANSISTOR WILL HAVE REACHED THE SIZE OF MERELY A FEW ATOMS, SIGNIFICANTLY HINDERING ADVANCEMENT IN TRADITIONAL COMPUTING. SO WHAT'S NEXT? IQC FACULTY MEMBER **GUO-XING MIAO** IS SEARCHING FOR AN ANSWER.

CREATING QUANTUM MATERIALS

Miao's research aims to develop materials useful for quantum information processing. One example is a topological insulator, potential host of Majorana Fermion particles that are self-protected by topology. The surface of this material is polarized and conducting, while the inside is insulating, creating an error-tolerant environment with almost no decoherence. This stability is advantageous for topological quantum information processing and may contribute to a robust semiconductor platform for running quantum algorithms – an important part of building a quantum computer.

[ONE LAYER AT A TIME]

The fabrication of materials development is a detailed and technical process. The topological quantum computing platform Miao is working on in his lab requires the integration of three distinct layers, each created separately. One of these layers is the magnetic insulator to induce spin selectivity.

Magnetic insulators have two interesting properties. First, they can selectively allow the passage of electrical current containing electrons with only one type of spin through them, called the spin-filtering effect. The second property – the ability to generate a very large effective magnetic field – occurs when they are interfaced with a low-dimensional electronic system. This field could be as large as tens of Tesla, which is equivalent to the largest continuous man-made magnetic fields.

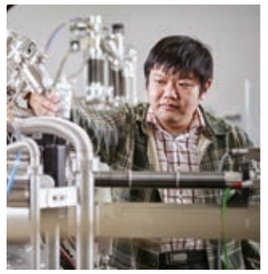
Recently, Miao and collaborators from the Korea Institute of Science and Technology (KIST), Northeastern University and the Massachusetts Institute of Technology (MIT) demonstrated a large effective magnetic field induced by a magnetic insulator and experimentally detected it.

These results could be practical for regulating spin flows in electronic devices, known as spintronics, which is useful for both classical and quantum information processing. The proven ability to locally generate a strong effective magnetic field may also be beneficial for practical device design by replacing the large superconducting magnets typically used in laboratory settings. "Despite its strength, it is easy to manipulate this magnetic field. It's similar to writing a data bit on a hard drive," said Miao. A nanometer-sized layer of materials deposited on a circuit can create a local magnetic field around a specific region, which could also be useful in engineering a topological insulator.

[TO BUILD A QUANTUM COMPUTER]

The ultimate goal is to create a real, tangible and scalable quantum computer – the next generation of processors, after Moore's Law reaches its limit. "This is one step towards realizing a topological quantum computer," said Miao. "Further materials development is needed. This is a mission that we are committed to."

WEB *Spin regulation in composite spin-filter barrier devices:* **http://bit.ly/spintronics**



THE VIEW FROM HERE

Postdoctoral fellow **HUI ZHANG** has been studying physics and chemistry ever since his middle school days. After completing his Master's degree and PhD in condensed matter physics at the University of Science and Technology of China, Zhang traveled to Canada to pursue postdoctoral research in quantum materials and quantum information at IQC. This was his first trip to Canada; as an avid astronomer he was impressed by the Canadian night sky and its clear view of the constellations.

Zhang works in the lab with faculty member **GUO-XING MIAO**, developing topological insulator materials for processing quantum information. He is working on a multi-layer film consisting of a magnesium diboride superconductor, a rare-earth chalcogenide magnetic insulator and a topological insulator made from bismuth, antimony and tellurium. Combined, these layers make a heteroepitaxial structure that will be used to build a novel quantum-nano semiconductor device with trijunction nodes, fabricated in the Quantum NanoFab facility in the Mike & Ophelia Lazaridis Quantum-Nano Centre. "The device could generate Majorana Fermion particles useful for topological quantum information processing, at the interface between a topological insulator and a superconductor. This may be considered as a robust semiconductor platform for decoherence-free quantum information processing and novel quantum algorithms," said Zhang.

With plans to continue his research in condensed matter physics and quantum materials, Zhang hopes to find more applications in quantum materials for quantum computing. Transition metal sulfides, he notes, is another interesting area of materials showing potential in this field. "That is something I hope to explore further."

BRIDGING THE FUNDAMENTAL TO THE APPLIED

THEORETICAL PHYSICS, RELATIVITY AND QUANTUM INFORMATION THEORY SEEMED FASCINATING AND EVEN MAGICAL TO **EDUARDO MARTÍN-MARTÍNEZ** AS A YOUNG CHILD. BORN NATURALLY CURIOUS, MARTÍN-MARTÍNEZ FOUND THE UNKNOWN INTRIGUING.

Now, as an IQC researcher, Martín-Martínez investigates a relatively new realm of quantum information that investigates fundamental questions about our universe: relativistic quantum information (RQI). RQI is the union of two fields: the theory of relativity, which predicts that the same laws of light and gravity are applied everywhere, and quantum information theory, which looks at the flow of information and strives to harness quantum science to build technologies for processing information. RQI uses knowledge and approaches from quantum information to study gravity and the structure of space-time.

[QUANTUM COLLECT CALLING]

In a recent paper, Martín-Martínez in collaboration with IQC Associate **ACHIM KEMPF** and PhD student **ROBERT JONSSON** from the Department of Applied Mathematics at the University of Waterloo, found a possible communication channel that does not require energy transmission from the sender to the receiver, but instead requires only the receiver to spend energy to run its detector, similar to a collect call.

The team of researchers proved that after some type of signal passes, such as a beam of light, there is information left as an afterglow – like an echo – that remains after the beam is long gone. This echo can be tapped into, allowing for the transmission of information not supported by an energy flow. Since it is the receiver who spends the energy to read the information carried in the echo, this kind of communication without energy exchange may be called "Quantum Collect Calling." This new type of communication channel makes it possible for the sender to transmit information without energy exchange, without the receiver being present to receive the signal and without spending extra energy to broadcast to many receivers.

WEB

Information Without Energy Exchange:
http://bit.ly/info-transmission-wout-energy

Violation of the Strong Huygen's Principle and Timelike Signals from the Early Universe:
http://bit.ly/timelike-signals-early-universe

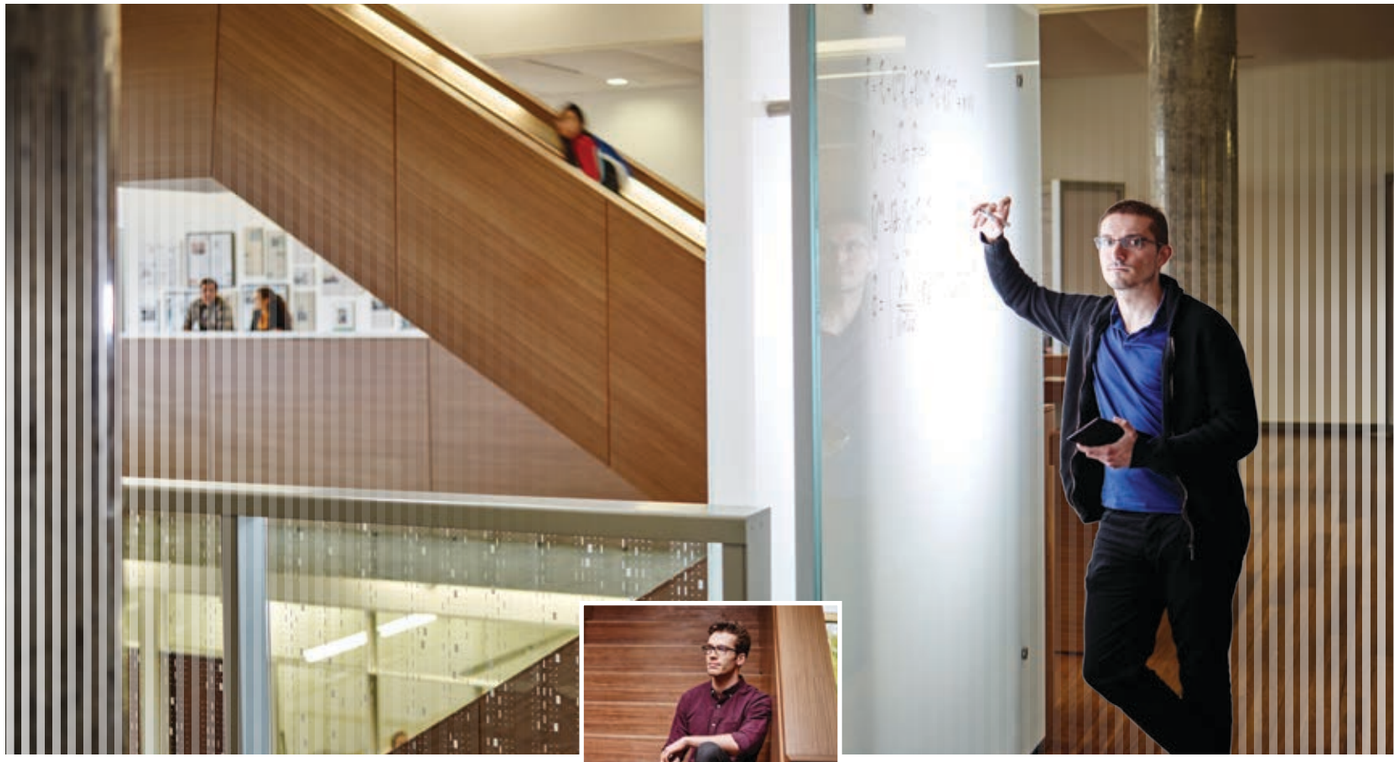
[A GLIMPSE OF THE EARLY UNIVERSE]

Following these results, Martín-Martínez and a group of international researchers from Spain and the Netherlands examined this new communication channel to see if it could be used to access information that was previously inaccessible from the early stages of the universe. In this proof of principle, the researchers showed that information transmitted through these echoes travels more resiliently than it would by light, only showing signs of decay over time and not over the distance between a past sender and the current receiver. Echoes traveling from the very start of the universe could shed some light on this event, providing helpful insight for cosmologists.

These results are fundamental, notes Martín-Martínez. The laws of physics show that it is possible and how, in principle, this information from the early universe can be recovered. Building an experiment for further exploration, including receivers to detect these echoes, is the next challenge, as well as an opportunity to collaborate with experimentalists.

[AN INTRIGUING FIELD OF RESEARCH]

Martín-Martínez wrote one of the very first theses on RQI and has watched the research community expand exponentially over the past decade. What he finds interesting is that often the outcomes from a fundamental study have direct, practical applications in technology and quantum information processing. "This broad scope," said Martín-Martínez, "is what's most exciting about RQI. It's an intriguing field, with many discoveries ahead."



QUANTUM CONTROL

DAVID LAYDEN's first experience at IQC was as a co-op student working in the lab with faculty member **ADRIAN LUPASCU**, characterizing decoherence in superconducting qubits. Now a Master's student in Applied Mathematics (Quantum Information), Layden works mostly on theoretical concepts in quantum information, but he keeps in mind the idea of implementing his research in a laboratory environment.

The Quantum Zeno Effect was one concept Layden explored with his supervisor, IQC Associate Member **ACHIM KEMPF**, also a professor in the Department of Applied Mathematics at the University of Waterloo, along with **EDUARDO MARTÍN-MARTÍNEZ**, IQC Research Assistant Professor. Preserving quantum information is fundamental for building a quantum computer. Decoherence interferes with this preservation. This leads to the deterioration of the quantum information in the states before it has been useful for any kind of computation or processing task. In contrast, the Quantum Zeno Effect occurs when frequent and perfect measurements of a system actually prevent it from evolving, and in particular, from decohering. One way to perfectly preserve a system and prevent decoherence would be to measure it infinitely frequently – an approach, however, that is not practical.

Layden, together with Kempf and Martín-Martínez, found a way to realize the same effect but in a more realistic setting, using imperfect measurements performed at a finite frequency. This may lead to practical applications in quantum computing where battling decoherence in quantum systems remains one of the main challenges.

Now, Layden's research is focused on quantum control, which involves coaxing a quantum system into evolving in a desired manner, a challenge given that most real systems are complex and noisy. "I plan to continue research in this field. Quantum information science and technology is an exciting and challenging research area," said Layden. "It's one that is changing rapidly."

A UNIQUE OFFERING AT THE UNIVERSITY OF WATERLOO, THE GRADUATE PROGRAM IN QUANTUM INFORMATION REFLECTS THE CROSS-DISCIPLINARY RESEARCH AND COLLABORATION BETWEEN LEADING COMPUTER SCIENTISTS, ENGINEERS, CHEMISTS, MATHEMATICIANS AND PHYSICISTS AT IQC.

A MAGNET FOR THE WORLD'S BEST

PREPARING THE LEADERS OF THE NEXT QUANTUM REVOLUTION

Students in the program explore theoretical and experimental aspects of quantum information science through a wide range of advanced courses and research projects. Researchers from three faculties – Engineering, Mathematics and Science – unite to provide the resources and training to prepare future leaders in the field of quantum information.

I look back at the graduate program during 2014-15 with satisfaction. The graduate program continued to grow and attract outstanding students. IQC faculty received 9.6% more applicants, and our student population grew by 13.5%. About a third of the eligible students held NSERC scholarships. Three students received IQC achievement awards for their contributions to research in quantum information. We continued international student exchanges with leading European and Asian universities, and received a substantial three-year grant for supporting exchanges with the Centre for Quantum Technologies at the National University of Singapore. Our Master's and PhD graduates were recruited by top academic and private sector institutions.

I am proud of our students and their continued achievements in the field of quantum information. They are well-positioned to push the frontiers of this field, fueling the realization of real-world quantum technologies and contributing to fundamental developments that will benefit our society.

It has been an honour to guide the graduate program over the past two years. As my term as program director ends, I wistfully pass the stewardship of the graduate program to Professor **JOHN WATROUS**. He will no doubt continue building on its excellence.

Ashwin Nayak
Quantum Information Graduate Program Director, 2013-2015

COURSES

The University of Waterloo, in collaboration with the Institute for Quantum Computing, offers graduate students unique opportunities to learn about and engage in world-leading research in quantum information through a wide range of advanced research projects and advanced courses on the foundations, applications and implementation of quantum information processing.

FALL 2014

QIC 710
Quantum Information Processing

QIC 890
Spin-Based Implementations

QIC 890
Haar Measure in Quantum Information Theory

QIC 890
Modern Quantum Optics and Nanophotonics

QIC 891
Topics in Quantum-Safe Cryptography

WINTER 2015

QIC 750
Implementations of Quantum Information Processing

QIC 885
Quantum Electronics and Photonics

QIC 890
Implementations of Quantum Communication

QIC 845
Open Quantum Systems

QIC 823
Quantum Algorithms

SPRING 2015

PHYS 777
Sir Anthony Leggett Lecture Series: Condensed Matter Theory from a Quantum Information Perspective

QIC 890/891
Selected Advanced Topics in Quantum Information

QIC 891
Topics in Quantum-Safe Cryptography

QIC 895
Theory of Quantum Optics




IQC GRADUATE STUDENT ASSOCIATION

IT WAS AN ACTIVE YEAR FOR IQC'S GRADUATE STUDENT ASSOCIATION (GSA), STARTING OFF WITH A SCREENING OF THE OSCAR-WINNING MOVIE *GRAVITY* WITH FORMER ASTRONAUT AND PRESIDENT OF THE CANADIAN SPACE AGENCY, **STEVE MacLEAN**, ALSO AN IQC ASSOCIATE MEMBER. AMONG SOCIAL ACTIVITIES LIKE LASER TAG, A TRIP TO CANADA'S WONDERLAND, PAINTBALL, BOWLING, BOARD GAME NIGHTS, AN INTERNATIONAL POTLUCK AND AN INSTITUTE-WIDE CHILI COOK OFF, THE IQC GSA ALSO ORGANIZED THE QUANTUM INDUSTRY LECTURE SERIES FOR ITS MEMBERS. IQC ALUMNI **JONATHAN HODGES**, **PHIL KAYE** AND **NATHAN WIEBE** RETURNED TO SHARE THEIR EXPERIENCES PURSUING RESEARCH CAREERS, ENCOURAGING STUDENTS TO EXPLORE OPPORTUNITIES IN BOTH ACADEMIC AND INDUSTRY SETTINGS.

[GRADUATES]

CONGRATULATIONS TO OUR 2014 GRADUATES

Megan Agnew
MSc Physics (Quantum Information)

Shima Bab Hadiashar
MMath Combinatorics and Optimization (Quantum Information)

Jason Boisselle
MMath Applied Mathematics (Quantum Information)

Steven Casagrande
MSc Physics

Grant Cleary
MSc Physics

Ben Criger
PhD Physics

Aimee Gunther
MSc Physics (Quantum Information)

Deny Hamel
PhD Physics

Amir Jafari Salim
PhD Electrical and Computer Engineering (Quantum Information)

Stacey Jeffery
PhD Computer Science

Robin Kothari
PhD Computer Science

Stephane Labruyere
MASc Electrical and Computer Engineering (Quantum Information)

Om Patange
MSc Physics

Ansis Rosmanis
PhD Computer Science

William Stacey
MSc Physics (Quantum Information)

Lydia Vermeyden
MSc Physics (Quantum Information)

Srinivasan Arunachalam
MMath Combinatorics and Optimization (Quantum Information)

Vadym Kliuchnikov
PhD Computer Science (Quantum Information)

Adam Paetznick
PhD Computer Science (Quantum Information)

Daniel Puzzuoli
MMath Applied Mathematics (Quantum Information)

Kyle Willick
MSc Physics (Quantum Information)

Amin Eftekharian
PhD Electrical and Computer Engineering

Milad Khoshnegar
PhD Electrical and Computer Engineering

[GRADUATE STUDENTS] 2014-2015

Sascha Agne
Megan Agnew
Rubayet Al Maruf
Thomas Alexander
Omar Alshehri
Vadiraj Ananthapadmanabha Rao
Elena Anisimova
Razieh Annabestani
Juan Miguel Arrazola
Srinivasan Arunachalam
Shima Bab Hadiashar
Golam Bappi
Marie Barnhill
Ryan Barrage
Jeremy Bejanin
Marian Berek
Jason Boisselle
Arnaud Carignan-Dugas
Steven Casagrande
Poompong Chaiwongkhot
Chung Wai Sandbo Chang
Paulina Corona Ugalde
Alessandro Cosentino
Hillary Dawkins
Chunqing Deng
Rahul Deshpande
Olivia Di Matteo
John Donohue
Carolyn Earnest
Kent Fisher
Jeremy Flannery
Honghao Fu
Zhiwei Gao
Naimeh Ghafarian
Kaveh Gharavi
Mirmojtaba Gharibi
Nicolas Gonzalez
Christopher Granade
Matthew Graydon
Peter Groszkowski
Aimee Gunther
Vibhu Gupta
Holger Haas
Minyang Han
Fatin Haque
Ian Hincks
Catherine Holloway
Gregory Holloway
Darryl Hoving
Anqi Huang
Vinay Iyer
Amir Jafari Salim
Stacey Jeffery
Yuantao Ji
Tomas Jochym-O'Connor
Oleg Kabernik
Sarah Kaiser
Shitikanth Kashyap
Hemant Katiyar
Sumeet Khatri
Maria Kieferova
Feyruz Kitapli
Vadym Kliuchnikov
Robin Kothari
Anirudh Krishna
Meenu Kumari
Stephane Labruyere
David Layden
Han Le
Lin Li
Madelaine Liddy
Piers Lillystone
Kevin Liu
Li Liu
David Lou
David Luong
Xian Ma
Jean-Philippe MacLean
Michael Mazurek
Thomas McConkey
Corey Rae McRae
Evan Meyer-Scott
Maryam Mirkamali
Hamidreza Nafissi
Takafumi Nakano
Tyler Nighswander
Mohamad Niknam
Matthew Novenstern
Joachim Nsofini
Jean-Luc Orgiazzi
Martin Otto
Alex Parent
Kyungdeock Park
Jihyun Park
Christopher Pugh
Daniel Puzzuoli
Hammam Qassim
Sadegh Raeisi
John Rinehart
Nayeli Azucena Rodriguez Briones
Ansis Rosmanis
Vincent Russo
Shihan Sajeed
Jeff Salvail
Yuval Sanders
Dusan Sarenac
John Schanck
Behrooz Semnani
Ala Shayeghi
Feiruo Shen
Sumit Sijher
William Stacey
Nigar Sultana
Yongchao Tang
Alexander Valtchev
Guillaume Verdon-Akzam
Lydia Vermeyden
Sean Walker
Zimeng Wang
Chunhao Wang
Zak Webb
Kyle Willick
Christopher Wood
Yihang Yang
Joshua Young
Muhammet Yurtalan

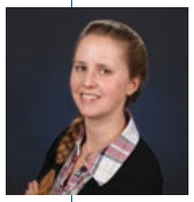
[POSTDOCTORAL FELLOWS] AS OF MARCH 31, 2015

Jean-Francois Biasse
Troy Borneman
Jean-Philippe Bourgoin
Aharon Brodutch
Patrick Coles
Joshua Combes
Electra Eleftheriadou
Guanru Feng
Pol Forn-Diaz
Denis Gagnon
Vlad Gheorghiu
Patryk Gumann
Gus Gutoski
Christopher Haapamaki
Christopher Herdman
Brendon Higgins
Rolf Horn
Mark Howard
Zhengfeng Ji
Jeongwan Jin
Nathaniel Johnston
Kassem Kalach
Milad Khoshnegar
Sangil Kwon
Ying Liu
Chang Liu
Dawei Lu
Filippo Miatto
Taisiya Mineeva
Osama Moussa
Ryo Namiki
George Nichols
Robabeh Rahimi Darabad
Daryoush Shiri
Fang Song
Rainer Stohr
Toeno van der Sar
Joel Wallman
Guoming Wang
Huan Yang
Taehyun Yoon
Nengkun Yu
Yanbao Zhang
Hui Zhang

IQC ALUMNI

ANNE BROADBENT

POSTDOCTORAL FELLOW 2013



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

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

NATHAN WIEBE

POSTDOCTORAL FELLOW 2013

NATHAN WIEBE, currently an Associate Researcher in the Quantum Architectures and Computation group at Microsoft Research, finished his postdoctoral fellowship at IQC in 2013. Since then he has continued his research on quantum simulation algorithms and the foundations of quantum thermodynamics, and ventured into quantum machine learning algorithms and quantum circuit synthesis.

Wiebe credits his time at IQC for the opportunity to build connections with world-renowned researchers who exposed him to new ideas, an experience that has contributed to his chosen career path in industry research. The IQC Graduate Student Association invited Wiebe back to IQC in October to share his experience in industry research with current graduate students as part of the Quantum Industry Lecture Series. Looking ahead, Wiebe predicts the landscape and scope of quantum information research to continue changing as more industry partners invest in the field.

URBASI SINHA

POSTDOCTORAL FELLOW 2012

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

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

Sinha expects to see exceptional progress in quantum information science experiments, theories and simulations over the next five to 10 years, predicting advances in error correction by solid state qubit researchers as well as an increasing number of novel qubits used in quantum information processing which will cumulatively bring us a step closer to the quantum computer.

AWARDS AND RECOGNITION

FROM APRIL 1, 2014 TO MARCH 31, 2015

FACULTY AWARDS AND GRANTS

MATTEO MARIANTONI
Early Researcher Award
(April 2014)

EDUARDO MARTÍN-MARTÍNEZ
John Charles Polanyi Prize
(November 2014)

ASHWIN NAYAK
Queen Elizabeth II Diamond Jubilee Scholarship
(March 2015)

JOHN WATROUS
NSERC Discovery Accelerator Supplement
(July 2014)

CHRISTOPHER WILSON
Early Researcher Award
(April 2014)

STUDENT AWARDS

EARNED BY IQC MASTER'S AND PHD STUDENTS IN THE 2014-15 FISCAL YEAR

DAVID R. CHERITON GRADUATE SCHOLARSHIP

Juan Miguel Arrazola

IQC ACHIEVEMENT AWARD

Vadiraj Ananthapadmanabha Rao
Juan Miguel Arrazola
John Donohue
Tomas Jochym-O'Connor
Robin Kothari

IQC DAVID JOHNSTON AWARD FOR SCIENTIFIC OUTREACH

John Donohue
Aimee Gunther
Corey Rae McRae

IQC ENTRANCE AWARD

Alessandro Cosentino
Hillary Dawkins
Honghao Fu
Vinay Iyer
Sumeet Khatri
Daniel Puzzuoli
Jeff Salvail
Kyle Willick

MIKE AND OPHELIA LAZARIDIS FELLOWSHIP

Maria Kieferova
Hammam Qassim

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP — DOCTORAL

John Donohue
Jeff Salvail
Kyle Willick

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP — MASTER'S

Hillary Dawkins
Vinay Iyer
David Layden

NSERC POSTGRADUATE SCHOLARSHIP — DOCTORAL

Gregory Holloway

NSERC VANIER CANADA GRADUATE SCHOLARSHIP

Tomas Jochym-O'Connor
Jean-Philippe MacLean

ONTARIO GRADUATE SCHOLARSHIP

Matthew Graydon
Aimee Gunther
Xingliang (David) Lou
Sean Walker
Chunhao Wang

PRESIDENT'S GRADUATE SCHOLARSHIP

Hillary Dawkins
John Donohue
Matthew Graydon
Aimee Gunther
Gregory Holloway
Vinay Iyer
David Layden
Xingliang (David) Lou
Jeff Salvail
Sean Walker
Chunhao Wang
Kyle Willick

QEII-GRADUATE SCHOLARSHIP IN SCIENCE AND TECHNOLOGY

Jihyun Park

LIKE OTHERS STUDYING QUANTUM INFORMATION SCIENCE AT IQC, **LAURA DE DECKER** WORKS THROUGH QUANTUM MECHANICAL EQUATIONS AND PROBLEMS. YET, AS IQC'S ARTIST IN RESIDENCE, SHE TACKLES THEM WITH A UNIQUE OBJECTIVE. DE DECKER CREATES IMAGES THAT ARTISTICALLY INTERPRET OR USE QUANTUM PHENOMENA, SUCH AS ENTANGLEMENT, SUPERPOSITION AND RANDOMNESS.

QUANTUM TRANSLATIONS

ARTIST IN RESIDENCE LAURA DE DECKER TAKES AN ARTISTIC TWIST ON THE QUANTUM REALM

> "I AM TRANSLATING THE MATH OF QUANTUM MECHANICS INTO COLOUR AND FORM."
>
> LAURA DE DECKER,
> IQC, ARTIST IN RESIDENCE

[AN ARTISTIC TWIST ON THE QUANTUM REALM]

Art-making is something that De Decker has enjoyed from a young age. Influenced by her grandfather's love for painting, she developed a passion for art creation growing up in Tillsonburg, Ontario in a house filled with books and chalkboards. At first she used traditional media to create art, mainly painting and sculpture, but soon found her true interest: exploring colour and form.

De Decker found that computer programming was the perfect way to bring those ideas together. She taught herself the programming language Visual Basic while finishing her Master of Fine Arts in Visual Arts at the University of Victoria, and then expanded those skills during the completion of a post-graduate certificate in Interactive Multimedia from Sheridan College. She went on to teach in Sheridan's Communication, Culture, Information and Technology Program. Since then she has continued to use tools such as mathematics, computer programming and technology to express herself artistically.

De Decker's father, a graduate of the University of Waterloo's physics and astronomy department and now a retired high school math and science teacher, encouraged natural curiosity and exploration. She became a science enthusiast, interested in learning how the world around us works.

Last year, De Decker was presented with an opportunity to combine her love of both art and science when she was awarded a 2015 Ontario Arts Council Chalmers Arts Fellowship research grant to work with IQC Executive Director **RAYMOND LAFLAMME** at Waterloo. The purpose of the grant is to explore ideas that will benefit her career beyond the creation of current artworks. Her objective: to lay the groundwork to create artistic interpretational images of quantum phenomena as large format prints and video animation.

With only a brief introduction to quantum mechanics during a university chemistry course, the subject is new to De Decker. She meets weekly with Laflamme and reads books about it. "IQC is a good environment for me. I have connected with many researchers, students and staff. There is lots of help nearby if I get stuck on a problem," says De Decker.

And yes, she is actually working through mathematical calculations – except her end goal is to create artistic work. "I am translating the math of quantum mechanics into colour and form," describes De Decker. "At this point, knowing the computer programming commands is not an issue, the challenge is understanding the math and what it represents and translating it into computer code." Using a small amount of computer code through a process of distillation by making schematic sketches, calculations and intuitive processes she has developed over the past fifteen years, she changes the mathematical variables to create and build images.

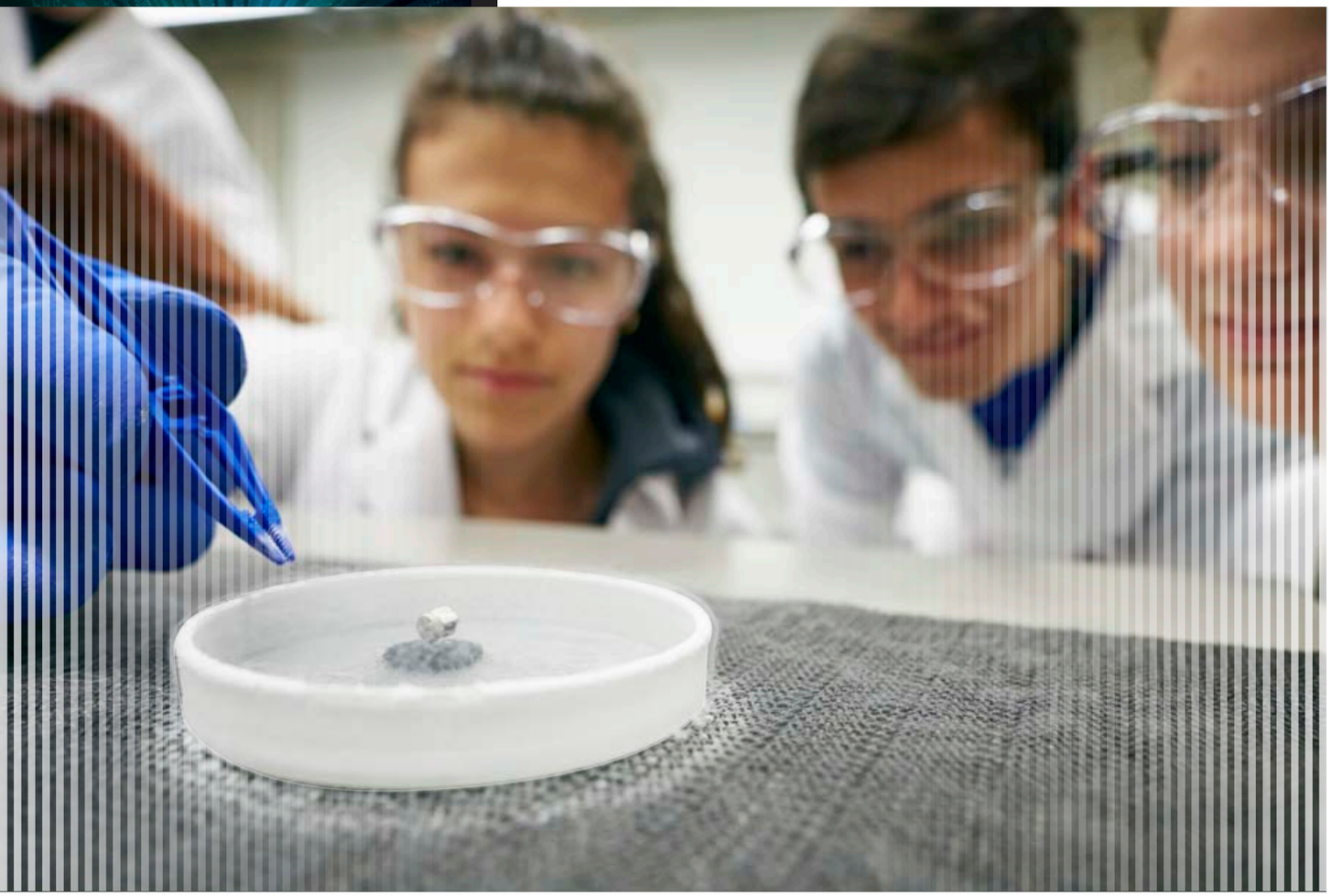
Although she's new to the science, De Decker sees similarity between art and the quantum realm. "Learning about quantum phenomena naturally extends from my interest in colour and geometry," she notes. "My work comes out of a Minimalist tradition, which is very material and theoretic; it tries to get at the essence of things. I'm interested in understanding the fundamental so that I can create complex forms, and quantum mechanics is also fundamental."

De Decker is envisioning how her final works will look. The idea is to create artwork that will be exhibited. "I hope my excitement about quantum mechanics comes through the art I create," she says. "Being Artist in Residence at IQC has been a wonderful opportunity. I'm so lucky to get to work with Professor Laflamme, he's a really interesting person and I am learning a lot from him. I'm also thankful for the support of the Ontario Arts Council Chalmers Arts Fellowship research program."

De Decker's existing work exploring the optical mixing of colour is on display in the *LIGHT Illuminated* show at THEMUSEUM, and new work will be part of an exhibition at the Kitchener-Waterloo Art Gallery during the summer of 2016.

ABOUT LAURA DE DECKER

Laura De Decker's work has been presented across the country, including Banff New Media Institute, Toronto's Red Head Gallery, Ed Video Media Arts Centre (Guelph), Factory Media Centre (Hamilton) and with Penderecki String Quartet's Quantum to Cosmos Festival performance at the Perimeter Institute for Theoretical Physics (Waterloo). In 2012 she was the first Christie Digital/Contemporary Art Forum, Kitchener + Area (CAFKA) Artist in Residence. Last year, she exhibited a video animation and presented a paper at the 20th International Symposium on Electronic Art (ISEA 2014) hosted by Zayed University in Dubai. Her work is in the collection of the University of Waterloo Stratford Campus and in private collections across Canada and Europe.



SCIENTIFIC OUTREACH

SHARING, EDUCATING, INSPIRING, CONNECTING. IQC BRINGS THE WORLD OF QUANTUM INFORMATION SCIENCE AND TECHNOLOGY TO THE CURIOUS-MINDED THROUGH UNIQUE OUTREACH OPPORTUNITIES DESIGNED TO SHARE THE FASCINATING RESEARCH THAT IS CHANGING THE WAY WE LIVE, WORK AND PLAY.

[RECOGNIZING COMMUNITY OUTREACH AND ENGAGEMENT]

Congratulations to **JOHN DONOHUE**, **AIMEE GUNTHER** and **COREY RAE MCRAE**, winners of the 2014 IQC David Johnston Award for Scientific Outreach. This award was created in honour of His Excellency **DAVID JOHNSTON**, Canada's Governor General, for his passion, leadership and enthusiasm for continuous learning, innovation and achievement. David Johnston was president of the University of Waterloo from 1999 to 2010. Up to three awards valued at $2,500 each, funded by Industry Canada, are given annually to current graduate students at IQC who have shown an outstanding commitment to scientific outreach and community engagement.

JOHN DONOHUE

For more than three years, PhD student **JOHN DONOHUE** has been involved with Let's Talk Science at the University of Waterloo. He actively volunteers for IQC open houses and high school visits, and also helps out with the Undergraduate School on Experimental Quantum Information Processing (USEQIP) and the Quantum Cryptography School for Young Students (QCSYS).

"Teaching and involving young people in science is a different challenge than what one finds in a lab. Breaking down big concepts into bite-size chunks puts into focus the reason we do what we do," says Donohue, who also enjoys sharing his passion for science with others. Donohue's research is in ultrafast photonics, using strong pulsed lasers to manipulate the shape of the wavepacket of entangled photons.

AIMEE GUNTHER

PhD student **AIMEE GUNTHER** remembers a middle school visit to a microwave telescope observatory where she learned about physics and astronomy from a postdoctoral researcher. Now as a PhD student, her own research focuses on quantum and nonlinear optics, investigating applications of energy-time entanglement into biological imaging and sensing.

She participates in science outreach activities for all ages, including the Canadian Association of Girls in Science (CAGIS) and local and regional science fairs at the elementary school level. At IQC she helps out with the Quantum Cryptography School for Young Students (QCSYS), the Catalyst Summer Leadership Program, tours for high school students and IQC Open Houses. In 2013, Gunther was part of the International Women's Day Women in Science event for members of the community.

Gunther values the skills she has gained through her volunteer experiences and has since enrolled in a Certificate of University Teaching course. She has even planned her own science outreach events, such as the 2013 Canadian American Mexican Graduate Student Conference and most recently, leading a team of graduate students to fund and curate a museum exhibit on light and light-based technologies.

COREY RAE McRAE

While growing up, participating in science outreach programs such as Go Eng Girl and CAGIS sparked **COREY RAE MCRAE**'s interest in science, leading her down the path to continue studying in this field. Now a PhD student at IQC, McRae is researching the nanofabrication techniques used to manufacture superconducting quantum circuits. During her two-year term as president of the IQC Graduate Student Association, McRae founded the Quantum Industry Lecture Series and the Student Entrepreneurship Group at IQC.

McRae recognizes the importance of science outreach and actively volunteers her time to encourage science discovery for youth, in particular for young females. She has been involved in organizing field trips to IQC for CAGIS, volunteering at IQC Open Houses, participating on a panel at the Canadian Conference for Undergraduate Women in Physics and volunteering at the International Conference for Women in Physics.

[ENCOURAGING YOUTH TO EXPLORE QUANTUM INFORMATION SCIENCE]

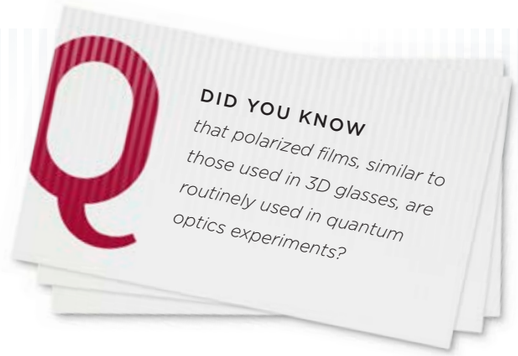
IQC CONTINUES TO EDUCATE AND EXCITE STUDENTS ABOUT QUANTUM INFORMATION SCIENCE AND TECHNOLOGY (QIST) THROUGH HANDS-ON WORKSHOPS, LECTURES AND LAB TOURS. THIS YEAR:

46
OUTREACH ACTIVITIES FOCUSED ON QUANTUM INFORMATION SCIENCE

2500+
STUDENTS AND COMMUNITY MEMBERS WERE INTRODUCED TO QIST

1600+
YOUTH PARTICIPATED IN A HANDS-ON WORKSHOP, LAB TOUR OR LECTURE

165
SCHOOL TEACHERS RECEIVED THE TOOLS TO SHARE QUANTUM INFORMATION WITH STUDENTS IN THEIR CLASSROOM



UNDERGRADUATE SCHOOL ON QUANTUM INFORMATION PROCESSING

MAY 26-JUNE 2, 2014

Twenty-one undergraduate students from nine countries came to IQC to explore both the theoretical and experimental aspects of quantum information for two weeks at the Undergraduate School on Quantum Information Processing (USEQIP). Students spent time in the labs working on experiments with IQC members and also had the opportunity to attend lectures by IQC faculty **RAYMOND LAFLAMME**, **DAVID CORY**, **MICHELE MOSCA**, **MICHAL BAJCSY**, **JONATHAN BAUGH**, **ANDREW CHILDS**, **THOMAS JENNEWEIN**, **KEVIN RESCH** and **CHRISTOPHER WILSON.** Twelve of the participants spent the rest of the summer at IQC to perform research.

QUANTUM CRYPTOGRAPHY SCHOOL FOR YOUNG STUDENTS

AUGUST 11-15, 2014

Through lectures and in-lab demonstrations, 42 grades 11 and 12 high school students from six Canadian provinces and five different countries traveled to IQC for the week-long Quantum Cryptography School for Young Students (QCSYS) in August. Led by Senior Manager, Scientific Outreach **MARTIN LAFOREST**, students explored physics and mathematics of quantum mechanics, cryptography and how they merge into one of the most exciting topics in contemporary science – quantum cryptography.

CAGIS INSPIRES GIRLS TO DISCOVER QUANTUM

Two groups of young girls from the Guelph-Kitchener-Waterloo chapters of the Canadian Association for Girls in Science (CAGIS), a group for girls ages 8-12 who are interested in science, came to IQC in May and January to learn about quantum information science and technology. Led by Master's student **OLIVIA DI MATTEO** and PhD students **RAZIEH ANNABESTANI**, **CAROLYN EARNEST**, **AIMEE GUNTHER**, **SARAH KAISER**, **JOEL KLASSEN** and **COREY RAE MCRAE**, the young science enthusiasts used lasers to learn about quantum cryptography and played with the levitating superconducting train to learn about superconducting qubits. They were also guided through interactive demonstrations exploring algorithms, search algorithm efficiency and optics. Making liquid nitrogen ice cream was a highlight for both groups!

[CONFERENCES, WORKSHOPS AND SEMINARS HIGHLIGHTS]

6th INTERNATIONAL SUMMER SCHOOL AND CONFERENCE ON POST-QUANTUM CRYPTOGRAPHY

Summer School: SEPTEMBER 29-30, 2014 | Conference: OCTOBER 1-3, 2014

The Post-Quantum Cryptography Summer School at IQC focused on cryptography in a quantum era, introducing approaches to providing cryptographic tools that may be safe against quantum algorithmic attacks. Following the summer school, the PQCrypto conference created discussion about the need for standardizing quantum-resistant cryptography with researchers spanning all areas of quantum information science from different institutions.

ETSI 2ND QUANTUM-SAFE CRYPTO WORKSHOP

OCTOBER 6-7, 2014

IQC partnered with the European Telecommunications Standards Institute (ETSI) to present the 2nd annual ETSI Quantum-Safe Crypto workshop in Ottawa from October 6-7. Ninety-two attendees from the diverse communities of industry, government and academia met to discuss the standardization and deployment of the next-generation cryptographic infrastructure – specifically, one that will be secure against emerging quantum computing technologies. IQC board member and CEO of Approach Infinity Inc., **MARK PECEN**, presented the ETSI Quantum-Safe whitepaper. **CORINNE CHARETTE**, Chief Information Officer of the Government of Canada, was among the invited speakers.

QUANTUM INNOVATORS

OCTOBER 6-8, 2014

Fifteen promising young researchers in the fields of quantum physics and engineering came together for the 3rd Quantum Innovators workshop, hosted at IQC, to share their research and foster new connections. Invitees heard from **TERRY MCMAHON** (Dean, Faculty of Science, University of Waterloo) and **PEARL SULLIVAN** (Dean, Faculty of Engineering, University of Waterloo) about research excellence at Waterloo. Several postdoctoral fellows also spoke including **TROY BORNEMAN**, **AHARON BRODUTCH**, **ROBABEH RAHIMI DARABAD**, **CHRISTOPHER HAAPAMAKI**, **ROLF HORN**, **TOENO VAN DER SAR** and **ANDREAS FOGNINI** (TU Delft, Netherlands).

QUANTUM FRONTIERS DISTINGUISHED LECTURES

The Quantum Frontiers Distinguished Lecture series brings world-leading quantum researchers to share their research and knowledge with students and faculty at IQC and the University of Waterloo.

WHAT ROLE DOES QUANTUM MECHANICS PLAY IN BIOLOGY?

In September, **K. BIRGITTA WHALEY**, University of California, Berkeley and Lawrence Berkeley National Laboratory, described how the development of quantum mechanics in the early years of the twentieth century transformed both physics and chemistry, providing a new understanding of the microscopic behavior of atoms and molecules. The development of novel probes of living cells and the possible role of quantum mechanics in biological phenomena, such as photosynthesis, are being driven by advances in both quantum sciences and nanotechnology.

WEB *Watch the lecture:* **https://bit.ly/BirgittaWhaley**

FROM EINSTEIN TO WHEELER: WAVE PARTICLE DUALITY FOR A PHOTON

In October, **ALAIN ASPECT**, Institut d'Optique, École Polytechnique and CNRS Distinguished Scientist, presented on experiments he and his team realized with a true single photon source demonstrating that photons behave both like a wave and a particle. Such single photon sources are now an important resource in the domain of quantum information.

WEB *Watch the lecture:* **https://bit.ly/AlainAspect**

CYBERSECURITY IN A QUANTUM WORLD: WILL WE BE READY?

MARCH 10, 2015

A public lecture by IQC faculty member **MICHELE MOSCA** drew 150 community members interested in learning more about being cyber-safe in a quantum world. Mosca shared his predictions that with the possible realization of a quantum computer in 10 to 15 years, our current cybersecurity infrastructure will not keep our information safe and secure. He advised industry organizations to start planning for quantum-safe options and develop standards and quantum-safe tools. As individuals, Mosca suggested we share our security concerns with organizations that keep our data and ask questions about what is being done to keep our information secure – now and in the future.

WEB *Watch the lecture:* **http://bit.ly/cybersecurity-in-a-quantum-world-lecture**

[IQC ONLINE]

IQC BLOG: OUR QUANTUM WORLD
uwaterloo.ca/iqc/blog

Our quantum world is a blog written by quantum researchers for quantum researchers and those interested in their work.

THE QUANTUM LIBRARY
pubs.iqc.uwaterloo.ca

IQC's publications database is home to hundreds of peer-reviewed journal articles, conference proceedings, commentaries and other publications by IQC researchers. Searchable by author, publication, subject, keywords and other criteria, the site is an online repository of IQC's leading contributions to quantum information science.

YOUTUBE
youtube.com/quantumiqc

IQC's YouTube channel hosts more than 650 scientific talks, distinguished lectures and interviews with world-leading scientists. Watch our Quantum Researchers series featuring renowned researchers in the quantum information science field such as **ALAIN ASPECT**, **SERGE HAROCHE**, **SIR ANTHONY LEGGETT**, **NICOLAS GISIN**, **JANE E. NORHOLDT**, **JOHN PRESKILL** and **DAVID WINELAND**.

IQC WEBSITE
uwaterloo.ca/iqc

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

@QUANTUMIQC

QUANTUMIQC

A COLLABORATIVE APPROACH WITH GLOBAL REACH

IQC RESEARCHERS CONSIDER COLLABORATION A CATALYST FOR DISCOVERY, WORKING CLOSELY WITH PEERS FROM ORGANIZATIONS AROUND THE GLOBE. OUR INTERNATIONAL NETWORK CONTINUES TO EXPAND, MAKING CONNECTIONS THAT ARE LAYING THE GROUNDWORK FOR EXCITING FUTURE DEVELOPMENTS.

[NATIONAL & INTERNATIONAL AGREEMENTS]

IQC has signed eight official agreements to facilitate collaborative research projects, joint research projects, joint research and the pursuit of common scientific interests:

QUEBEC | **Institut National de la Recherche Scientifique**

QUEBEC | **Institut Transdisciplinaire d'Information Quantique**

CHINA | **Tsinghua University**

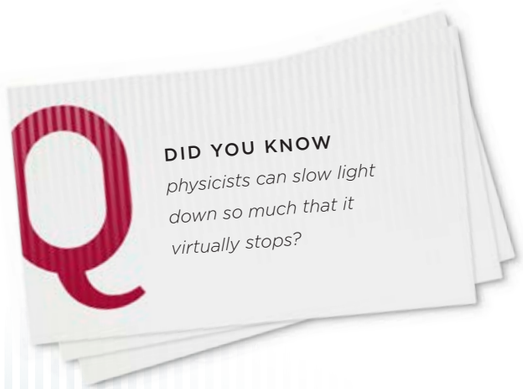
CHINA | **University of Science and Technology of China**

INDIA | **Raman Research Institute**

ISRAEL | **Technion - Israel Institute of Technology**

KOREA | **Korea Institute of Science and Technology**

SINGAPORE | **Centre for Quantum Technologies**



[INTERNATIONAL EXCHANGE]

The University of Waterloo supports exchange opportunities for IQC students, postdoctoral fellows and researchers that promote the advancement of education and research in quantum information processing through a student exchange agreement with the following institutions:

AUSTRIA | **Universität Innsbruck**

FRANCE | **École Normale Supérieure de Lyon**

FRANCE | **Université Paris Diderot**

GERMANY | **Friedrich-Alexander-Universität Erlangen-Nürnberg**

GERMANY | **Universität des Saarlandes**

LATVIA | **University of Latvia**

SINGAPORE | **National University of Singapore**

[MEETINGS]

QUANTUM INFORMATION SCIENCE PROGRAM MEETING

NOVEMBER 23-26, 2014

IQC, together with the Canadian Institute for Advanced Research (CIFAR), hosted a four-day meeting with prominent scientists from China to exchange ideas in quantum information science at the Lazaridis Centre in November. More than 50 delegates attended from the National Laboratory of Beijing Computational Science Research Centre (CSRC), the Interdisciplinary Information Sciences (IIIS) at Tsinghua University (also based in Beijing) and the University of Science and Technology of China (USTC) located in Hefei, Anhui.

ANNUAL MEETING OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

FEBRUARY 12-16, 2015

Thousands of scientists, engineers, policy makers, educators and journalists gathered in San Jose, California for the Annual Meeting of the American Association for the Advancement of Science (AAAS) in February. The University of Waterloo invited AAAS guests to its Global Innovation Showcase where IQC shared its research.

IQC researchers also participated in two sessions. Executive director **RAYMOND LAFLAMME** participated in a panel discussion titled Transformational Opportunities of Quantum Information Technologies, along with directors of other leading research institutes **ANDREW BRIGGS** (Quantum Information Processing Interdisciplinary Research Collaboration, England) and **ARTUR EKERT** (Centre for Quantum Technologies (CQT), National University of Singapore).

Research Assistant Professor **DMITRY PUSHIN** participated in a symposium on Wave-Particle Duality of Neutrons, Atoms and Molecules, presenting his work on the uniquely quantum behavior of a neutron interferometer.

WEB **http://bit.ly/AAAS2015_QIT**

IN 2014-2015, IQC RESEARCHERS:

COLLABORATED WITH **229** RESEARCHERS FROM **109** INSTITUTIONS IN **24** COUNTRIES

PARTICIPATED IN **84** CONFERENCES

WELCOMED **155** VISITORS FROM **108** LEADING INSTITUTIONS TO EXCHANGE IDEAS AND RESEARCH IN QUANTUM INFORMATION

VISITORS

RONALD RIVEST, RSA CO-INVENTOR | JUNE 13, 2014

RONALD RIVEST, co-inventor of the Rivest-Shamir-Adleman (RSA) public key encryption and digital signature schemes in 1977, was awarded an honourary Doctorate of Mathematics by the University of Waterloo in June. He toured IQC during his visit to Waterloo with IQC faculty member **MICHELE MOSCA** and Senior Manager, Scientific Outreach **MARTIN LAFOREST**, along with Professor **DOUG STINSON** from the David R. Cheriton School of Computer Science and Centre for Applied Cryptographic Research.

DELEGATION FROM THE TECHNION - ISRAEL INSTITUTE OF TECHNOLOGY | SEPTEMBER 18, 2014

For the first time since signing a co-operation agreement with the Technion - Israel Institute of Technology in March 2014, a delegation from Technion toured IQC on September 18. The partnership between IQC and the Technion aims to facilitate technology transfer, connect faculty and students with industrial partners and increase international opportunities for undergraduate, graduate and postdoctoral student research exchanges.

ALAIN ASPECT, CNRS DISTINGUISHED SCIENTIST OCTOBER 23, 2014

Centre national de la recherché scientifique (CNRS) distinguished scientist **ALAIN ASPECT** was awarded an honourary doctorate from the Faculty of Science, celebrated by a dinner hosted by IQC and the Faculty of Science. Among the dinner guests were Waterloo president **FERIDUN HAMDULLAHPUR**, Dean of Science **TERRY MCMAHON**, Associate Dean of Science, Graduate Studies **ROBERT HILL**, IQC faculty member **KEVIN RESCH** and Senior Manager, Scientific Outreach **MARTIN LAFOREST**. Two special guests included **MIKE LAZARIDIS** and **AINSLIE WATT**, the wife of the late Professor **LYNN WATT**. Professor Watt had presented one of Aspect's papers in a class attended by Lazaridis and it's what got him hooked on quantum mechanics.

FRANCE DELEGATION | NOVEMBER 13, 2014

A large delegation from France stopped in at IQC, touring the Quantum NanoFab facility and other labs during their visit. From the National Assembly, guests included **CATHERINE COUTELLE**, **CLAUDE GREFF**, **MARIE-NOÉLLE BATTISTEL**, **MICHÈLE BONNETON**, **JOËLLE HUILLIER** and **EMMANUELLE LAVIE**, along with Senate members: **PIERRE-YVES COLLOMBAT**, **JEAN-MARC TODESCHINI**, **JACKIE PIERRE** and **DELPHINE BERT**.

DELEGATION FROM THE REPUBLIC OF KOREA | NOVEMBER 21, 2014

AMBASSADOR CHO HEE-YONG toured IQC labs during a visit to Waterloo in November, a follow-up visit to an agreement signed with the Korea Institute of Science and Technology (KIST) in September. The agreement brings together two internationally recognized institutions to advance quantum science, aiming to accelerate the development of quantum technologies for the benefit of both countries.

[ACADEMIC & SCIENTIFIC VISITORS]

APRIL 1, 2014 TO MARCH 31, 2015

Raja Ahmad, McGill University
Erika Andersson, Heriot-Watt University
Anthony Ardizzi, University of Toronto
Sahel Ashhab, Qatar Foundation
Koji Azuma, NTT Basic Research Laboratories
Thomas Babinec, Stanford University
Shrobona Bagchi, Harish-Chandra Research Institute
Som Bandyopadhyay, Bose Institute
Stephen Bartlett, University of Sydney
Julien Bernu, Australian National University
Bhashyam Balaji, Defence Research and Development Canada
Joshua C. Bienfang, National Institute of Standards and Technology
Sergey Bravyi, IBM Research
Mitchell Brickson, Goshen College
Andrew Briggs, Oxford University
Paola Cappellaro, Massachusetts Institute of Technology
Christopher Chamberland, McGill University
Darrick Chang, Institute of Photonic Sciences
Joon-Yeon Chang, Korea Institute for Science and Technology
Franklin Cho, University of Southern California
Kai-Min Chung, Institute of Information Science, Academia Sinica
Christopher Chunnilall, National Physical Laboratory
JC Séamus Davis, Cornell University
Niel de Beaudrap, Centrum Wiskunde and Informatica
Nathalie de Leon, Harvard University
Franklin de Lima Marquezino, Federal University of Rio de Janeiro
Viatcheslav Dobrovitski, Iowa State University
Shuanping Du, University of Guelph
Ramy El-Ganainy, Michigan Technological University
Electra Eleftheriadou, University of Strathclyde
David Elkouss, Universidad Complutense de Madrid
Manuel Endres, Max Planck Institute of Quantum Optics in Garching
Jingyun Fan, National Institute of Standards and Technology
Omar Fawzi, Institute for Theoretical Physics ETH Zurich
Robert Fickler, University of Vienna
Austin Fowler, University of California, Santa Barbara
Ivette Fuentes, The University of Nottingham
Marko Gacesa, University of Connecticut
Vinzenz Gangl, UCP Plasma Technologies
Raul Garcia-Patron, Université Libre de Bruxelles
Sevag Gharibian, University of California, Berkeley
Genda Gu, Brookhaven National Laboratory
Sean Hallgren, Pennsylvania State University
Deny Hamel, University of Vienna
Angelica Harris, Government of Canada
Michael Hilke, McGill University
Jonathan Hodges, Diamond Nanotechnologies
Layla Hormozi, National University of Ireland
Masahiro Hotta, Tohoku University
Peter Hoyer, University of Calgary
Hannes Hübel, Stockholm University
Takashi Imai, McMaster University
Stacey Jeffery, California Institute of Technology
Jeongwan Jin, University of Calgary
Dilara Karakozak, Middle East Technical University
Maciej Karcz, Indiana University
Phil Kaye, Government of Canada
Viv Kendon, Joint Quantum Centre
Jens Koch, Northwestern University
Piotr Kolenderski, Nicolaus Copernicus University
Robin Kothari, Massachusetts Institute of Technology
Katanya Kuntz, University of New South Wales
Sun Kyung Lee, Korea Advanced Institute of Science and Technology
Thijs Laarhoven, Eindhoven University of Technology
Konstantinos Lagoudakis, Stanford University
Tom Lai, McGill University
Cedric Lin, Massachusetts Institute of Technology
Chang Liu, Hong Kong University of Science and Technology
Jorma Louko, The University of Nottingham
Frédéric Magniez, Université Paris Diderot
David McKay, University of Chicago
Nicolas C. Menicucci, University of Sydney
Carl A. Miller, University of Michigan
John Morton, University College London
Özgür E. Müstecaplioglu, Koç Üniversitesi
Casey Myers, University of Queensland
Matthieu Nannini, McGill University
Kae Nemoto, National Institute of Informatics
Valentin Nguyen, Université De Montréal
Masayuki Okano, Kyoto University
David P. Pappas, National Institute of Standards and Technology
Fernando Pastawski, California Institute of Technology
Vern Paulsen, University of Houston
Leon Pintsov, SignitSure Inc.
Xiaofei Qi, Shanxi University
Robert Raussendorf, University of British Columbia
Martin Roetteler, NEC Laboratories America Inc.
Jérémie Roland, Université Libre de Bruxelles
Terry Rudolph, Imperial College London
Romain Ruhlmann, McGill University
Mary Beth Ruskai, Tufts University
Or Sattath, University of California, Berkeley
Torsten Scholak, University of Toronto
Volkher Scholz, Institute for Theoretical Physics ETH Zurich
Yaoyun Shi, University of Michigan
Pragya Shukla, Indian Institute of Technology Kharagpur
Swati Singh, Harvard University
Rolando Somma, Los Alamos National Laboratory
Douglas Stebila, Queensland University of Technology
Dieter Suter, Technische Universität Dortmund
Krysta Svore, Microsoft Research
Alexander Szameit, Friedrich-Schiller-Universität Jena
Tae Hee Kim, Ewha Womans University
Kiyoshi Tamaki, NTT Basic Research Laboratories
Jeff Thompson, Harvard University
Joseph Thywissen, University of Toronto
Dave Touchette, McGill University
Joseph F. Traub, Columbia University
Adam Tsen, Columbia University
Dominique Unruh, University of Tartu
Joop van de Pol, University of Bristol
Prasanna Venkatesh, Pohang University of Science and Technology
Ty Volkoff, University of California, Berkeley
Petros Wallden, Heriot-Watt University
Jia Wang, University of Connecticut
Kejin Wei, Beijing University of Posts and Telecommunications
K. Birgitta Whaley, University of California, Berkeley
Nathan Wiebe, University of Calgary
Lianao Wu, University of the Basque Country
Xiaodi Wu, Massachusetts Institute of Technology
Feihu Xu, University of Toronto
Xiaodong Xu, University of Washington
Beni Yoshida, California Institute of Technology
Na Young Kim, Stanford University
Jingfu Zhang, Technische Universität Dortmund
Peter Zoller, University of Innsbruck
Val Zwiller, Delft University of Technology
Karol Życzkowski, Jagiellonian University

[LONG-TERM VISITORS]

APRIL 1, 2014 TO MARCH 31, 2015

Zhaofang Bai, Xi'an Jiaotong University
Eyal Buks, Technion-Israel Institute of Technology
Mehmet Canturk, Turgut Özal University
Rui Chao, Tsinghua University
Aixi Chen, Jiao Tong University
Kai-Min Chung, Institute of Information Science, Academia Sinica
Ben Criger, Institute for Quantum Information, RWTH Aachen University
Callum Croal, University of St. Andrews
Hyeran Kong, Pohang University of Science and Technology
Krtin Kumar, Indian Institute of Technology
Katanya Kuntz, University of New South Wales
Yury Kurochkin, Russian Quantum Center, Skolkovo
Anthony Leggett, University of Illinois at Urbana-Champaign
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Marta Palucka, Nicolaus Copernicus University
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Dominique Pouliot, University of Illinois at Urbana-Champaign
Moshen Razavi, University of Leeds
Kyung Soo Choi, Korea Institute of Science and Technology
Koon Tong Goh, Centre for Quantum Technologies
Paulo Vinícius Pereira Pinheiro, Federal University of Ceara
Gregor Weihs, University of Innsbruck
Tao Xin, Tsinghua University

IQC BY THE NUMBERS

APRIL 1, 2014 TO MARCH 31, 2015

[IQC IS HOME TO...]

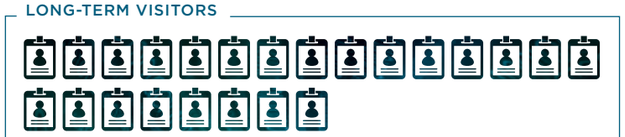
22 FACULTY MEMBERS

3 RESEARCH ASSISTANT PROFESSORS

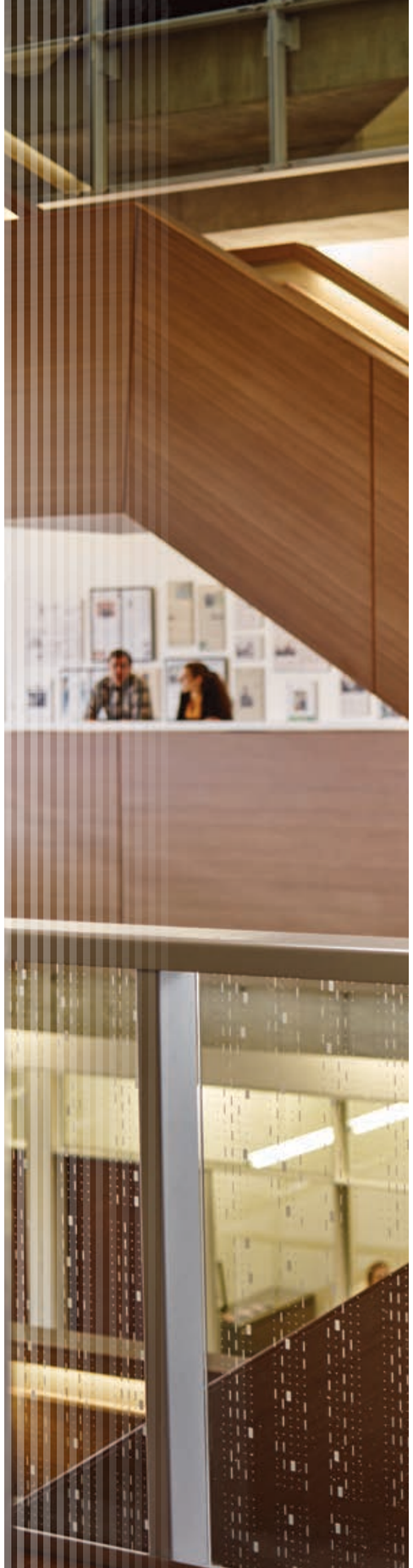
46 POSTDOCTORAL FELLOWS

126 GRADUATE STUDENTS

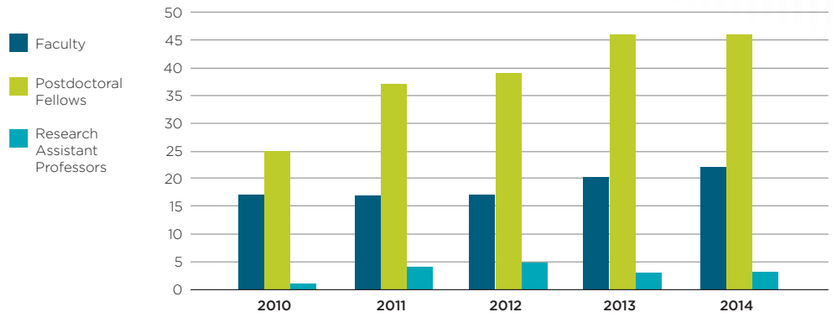
23 LONG-TERM VISITORS



7 TECHNICAL SPECIALISTS



[FACULTY & POSTDOCTORAL FELLOWS]



[PUBLICATIONS]

NOTABLE PUBLICATIONS

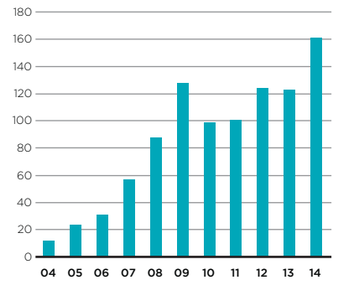
Notable publications in the journals *Nature*, *Nature Photonics*, *Nature Physics*, *Nature Communications*, *Physical Review Letters*, *Science*, *STOC*, *FOCS*, and the *Journal of Mathematical Physics* represent high-level, peer-reviewed discoveries by IQC researchers.

[IQC RESEARCH PUBLISHED IN PROMINENT JOURNALS SINCE 2007]

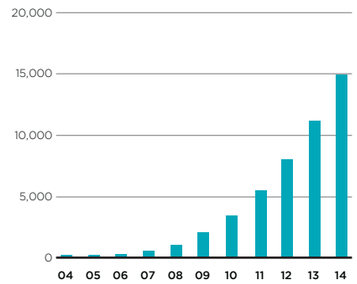
PUBLICATION	10-11	11-12	12-13	13-14	14-15
Nature	1	1	1		2
Nature Photonics	1	1		3	2
Nature Physics	5	3	2	3	
Nature Communications		1	1	1	5
Physical Review Letters	14	17	14	14	16
Science	1	2	1	1	3
STOC	2				
FOCS		1	1		
Journal of Mathematical Physics	2	4	6	4	4

The publication distribution listed above is collected from Thomson Reuter's ISI Web of Knowledge.

CUMULATIVE PUBLICATIONS BY IQC RESEARCHERS



CUMULATIVE CITATIONS OF IQC PUBLICATIONS



152 PUBLICATIONS BY IQC RESEARCHERS IN 2014

981 PUBLICATIONS BY IQC RESEARCHERS SINCE 2002

15,435 CUMULATIVE CITATIONS FOR ALL IQC PUBLICATIONS SINCE 2003

** Source for Publications and Citations: Thomson Reuters' Web of Science on April 2, 2015. Data compiled using an address search for Institute for Quantum Computing (inst* quant* comp*). Citations are cumulative for all IQC publications for all years.*

BUILDING WORLD-CLASS RESEARCH INFRASTRUCTURE

VITO LOGIUDICE,
DIRECTOR OF OPERATIONS,
QUANTUM NANOFAB

VITO LOGIUDICE, DIRECTOR OF OPERATIONS FOR THE QUANTUM NANOFAB, IS A SEASONED EXPERT WHEN IT COMES TO BUILDING CLEANROOMS FROM THE GROUND UP. AN ELECTRICAL ENGINEER BY TRADE, LOGIUDICE WAS IN THE MIDDLE OF HIS MASTER'S THESIS RESEARCH ON SOLAR CELLS AT CONCORDIA UNIVERSITY WHEN THE CLEANROOM HE WAS WORKING IN REQUIRED SOME EXTENSIVE RENOVATIONS. THROUGH HIS HANDS-ON INVOLVEMENT IN THE RENOVATION PROCESS, AND SUBSEQUENT YEARS OF INDUSTRY EXPERIENCE POST-GRADUATION, LOGIUDICE LEARNED ABOUT THE IMPORTANCE OF INFRASTRUCTURE AND A WORKING, WELL-MAINTAINED CLEANROOM FOR SUCCESSFUL RESEARCH. WORLD-CLASS INFRASTRUCTURE ENABLES WORLD-CLASS RESEARCH.

Now leading the Quantum NanoFab team, he focuses on achieving operational excellence to provide researchers with a controlled laboratory environment. The Quantum NanoFab is a state-of-the-art cleanroom and fabrication facility in the Mike and Ophelia Lazaridis Quantum-Nano Centre, a joint facility between IQC and the Waterloo Institute for Nanotechnology (WIN). The facility includes both Class-100 and Class-1000 spaces. The Class-100 cleanroom allows no more than 100 particles larger than 500 nanometers per cubic foot of air, creating an ultra-clean environment perfect for experimental research and device engineering.

"Nanofabrication can be complex and challenging," said Logiudice. "Rigorous maintenance ensures the equipment is always running as close to an optimal state as possible so that lab users can rely on it to perform repeatable processes every time. Aiming for excellence when it comes to the equipment, stability and process support is our research contribution. We enable lab users to build their devices as needed for their own scopes of research."

It takes a collaborative effort to keep the nanofabrication facility running smoothly. Logiudice credits the entire Quantum NanoFab team who keeps the machines operating, trains lab users, maintains the Class-100 and Class-1000 certifications, meets budget and provides funding accountability. The University of Waterloo's Plant Operations department also plays an instrumental role by providing essential services like stable and well-serviced ventilation systems, compressed air, high purity water and cooling water. "It's not a one-person activity. I have the privilege of leading this excellent group of people," noted Logiudice.

Looking ahead, the drive for excellence in supporting world-class research steers future goals for the Quantum NanoFab, which include:

Building additional fabrication capabilities. One example is the 100 keV electron beam lithography system, scheduled for installation in early 2016. This machine will allow researchers to reliably pattern structures down to only 8 nanometers wide – the equivalent of approximately 80 atoms.

Offering more process engineering support and fabrication services. The number of lab users will grow as cleanroom capabilities grow, emphasizing the need for more training. There's also an opportunity to offer fabrication services to remote customers and start-up companies in need of such services, where time to market is imperative.

This opportunity is one that excites Logiudice the most. WIN's **SIMARJEET SAINI**, also a professor in Waterloo's Department of Electrical and Computer Engineering, engineered an economical nanotech device in the Quantum NanoFab that can detect contaminated drinking water. "It's motivating to see what people can make via access to this facility," said Logiudice. "We provide the infrastructure, but to see the creative and successful use of its capabilities is exceptionally rewarding."

» The Quantum NanoFab team

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APRIL 1, 2014 TO MARCH 31, 2015

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Deputy Director, Research

Michele Mosca
Deputy Director

Robert E. Crow
Executive in Residence

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Director of Operations, Quantum NanoFab

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Mai-Britt Mogensen
Cleanroom Certification and Inventory Specialist

Nathan Nelson-Fitzpatrick
Nanofabrication Process Engineer

Roberto Romero
Electronics and Instrumentation Technologist and Health, Safety and Environment Coordinator

Rodello Salandanan
Senior Equipment Technologist

Matt Scott
Fabrication Equipment Technologist and Lab Instructor

Melissa Floyd
Accounting and Administrative Assistant

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Associate Director, Finance

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Administrative Coordinator/Financial Assistant

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Multimedia Coordinator

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Associate Director, Information Technology

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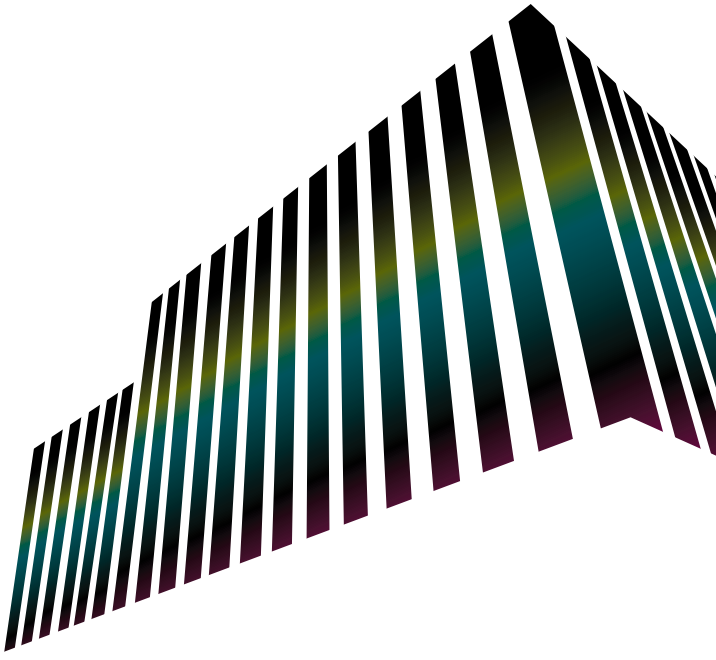
Computing Support Specialist

Matt Cooper
Information Technology Specialist

Ryan Goggin
Computing Support Specialist

Dylan Totzke
Computing Business Analyst

THANK YOU



IQC THANKS MIKE AND OPHELIA LAZARIDIS, THE PROVINCE OF ONTARIO AND THE GOVERNMENT OF CANADA FOR THEIR VISIONARY SUPPORT.

THANK YOU TO THE FOLLOWING INDIVIDUALS AND ORGANIZATIONS FOR THEIR GENEROUS AND CONTINUED SUPPORT OF IQC:

Alfred P. Sloan Foundation
American Physical Society Outreach
Army Research Office
Austrian Academy of Sciences
CERC (Canada Excellence Research Chairs)
CFI (Canada Foundation for Innovation)
CRC (Canada Research Chairs)
CIFAR (Canadian Institute for Advanced Research)
Canadian Space Agency
Canadian Queen Elizabeth II Diamond Jubilee Scholarship
COM DEV
Communications Security Establishment Canada
Connect Canada
C2C Link Corporation
DARPA (Defense Advanced Research Projects Agency)
Doug Fregin
Department of Canadian Heritage
ETSI (European Telecommunications Standards Institute)
FedDev (Federal Economic Development Agency for Southern Ontario)
FQXi (Foundational Questions Institute)
Government of Canada
IARPA (Intelligence Advanced Research Projects Activity)
Korean Institute of Science and Technology
Lockheed Martin Corporation
Mike and Ophelia Lazaridis
Mitacs
NSERC (Natural Sciences and Engineering Research Council)
Office of Naval Research
Ontario Centres of Excellence
Perimeter Institute for Theoretical Physics
Province of Ontario
Public Works and Government Services Canada
Quantum Valley Investments
Sandia National Laboratories
Technion Cooperation Program
The Gerald Schwartz & Heather Reisman Foundation

SPECIAL THANKS TO THE UNIVERSITY OF WATERLOO, IQC'S HOME, FOR SUPPORTING AND CELEBRATING RESEARCH, INNOVATION AND EXCELLENCE.

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing Ontario Canada