15 years
OF DISCOVERY & INNOVATION

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

annual report | 17

"WHAT'S HAPPENING HERE IN WATERLOO IS TRULY SPECIAL, FROM THEORY TO EXPERIMENT AND

BEYOND."

PROFESSOR STEPHEN HAWKING

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

THANK YOU

THE INSTITUTE FOR QUANTUM COMPUTING (IQC) THANKS MIKE AND OPHELIA LAZARIDIS, THE GOVERNMENT OF CANADA AND THE PROVINCE OF ONTARIO 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 | Canada Excellence Research Chairs (CERC) | Canada Foundation for Innovation (CFI) | Canada Research Chairs (CRC) | Canadian Institute for Advanced Research (CIFAR) | Canadian Space Agency | Canadian Queen Elizabeth II Diamond Jubilee Scholarship | COM DEV | Communications Security Establishment | Connect Canada | C2C Link Corporation | Defense Advanced Research Projects Agency (DARPA) | Doug Fregin | Department of Canadian Heritage | European Telecommunications Standards Institute (ETSI) | Federal Economic Development Agency for Southern Ontario (FedDev) | Foundational Questions Institute (FQXi) | Government of Canada | Intelligence Advanced Research Projects Activity (IARPA) | Korean Institute of Science and Technology (KIST) | Lockheed Martin | Mike and Ophelia Lazaridis | Mitacs | Natural Sciences and Engineering Research Council (NSERC) | Office of Naval Research | Ontario Centres of Excellence (OCE) | Perimeter Institute for Theoretical Physics | Province of Ontario | Public Services and Procurement 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.

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15 years OF DISCOVERY & INNOVATION

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Published by IQC Communications and Strategic Initiatives

INSTITUTE FOR QUANTUM COMPUTING

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UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

A DRIVE FOR Excellence & INNOVATION

Our 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 be a prime source of insight, analysis and commentary on quantum information.

Our vision

HARNESSING QUANTUM MECHANICS WILL LEAD TO TRANSFORMATIONAL TECHNOLOGIES THAT WILL BENEFIT SOCIETY AND BECOME A NEW ENGINE OF ECONOMIC DEVELOPMENT IN THE 21st CENTURY.

Our mission

TO DEVELOP AND ADVANCE QUANTUM INFORMATION SCIENCE AND TECHNOLOGY AT THE HIGHEST INTERNATIONAL LEVEL THROUGH THE COLLABORATION OF COMPUTER SCIENTISTS, ENGINEERS, MATHEMATICIANS AND PHYSICAL SCIENTISTS.

Core Research Areas

QUANTUM COMPUTING

Using atoms, molecules and particles of light to create new bits of computer information — qubits, which can be 0 and 1 at the same time — for computing.

QUANTUM COMMUNICATION

Developing ultra-secure communication channels, low-noise transmission protocols and satellite-based global networks by harnessing the power of the quantum world.

QUANTUM SENSING

Using the laws of quantum mechanics to develop new sensors with exponential precision, sensitivity, selectivity and efficiencies.

QUANTUM MATERIALS

Engineering materials that exhibit quantum properties for robust quantum information processors and other devices.

MAKING AN IMPACT

RESEARCH excellence

IQC ADVANCES THE MOST INNOVATIVE RESEARCH IN QUANTUM INFORMATION SCIENCE AND TECHNOLOGY.

298 researchers including **7** research chairs

1,506 publications since 2002

200+ active awards and grants, including **41** NSERC-funded grants and **6** CFI funded grants

Intellectual hub of activity

329 research collaborations spanning **34** countries and **180+** institutions in 2017

132 publications in 2017

30,357 cumulative citations

POTENTIAL IMPACT AREAS: ENVIRONMENT, PRIVACY, MEDICINE, TRANSPORTATION, TECHNOLOGY, DIGITAL COMMUNICATION

QUANTUM INFORMATION SCIENCE powerhouse

TAKING SCIENCE OUT OF THE LAB INSPIRES THE NEXT GENERATION OF SCIENTIFIC LEADERS.

Public education and engagement 2017 highlights

161,193 guests through *QUANTUM: The Exhibition* and *QUANTUM: The Pop-up Exhibition* at **13** locations in **14** months

4,826 participants in outreach programs promoting quantum information science and technology in 2017

1,301,458 minutes of quantum talks watched on YouTube in **200** countries

Scientific growth and training in 2017

HOSTED

4 conferences

4 workshops

42 seminars

24 colloquia

SPONSORED

15 workshops and conferences around the world

367 students engaged in lectures and hands-on learning

196 educators given the tools to integrate quantum into the classroom

QUANTUM ecosystem

THE WATERLOO REGION PROVIDES AN IDEAL ENVIRONMENT FOR ACADEMIC AND INDUSTRY PARTNERSHIPS. FUNDAMENTAL QUANTUM DISCOVERIES ARE ALREADY MOVING FROM THE LAB TO THE MARKET.

60+ patents & licenses by IQC researchers

7 spinoff companies

250+ researchers within 1 km of Waterloo working to advance the science, technology and commercial impact of quantum technologies

Alumni

68% in academia

21% in industry

35+ industry partnerships

AFTER A CENTURY STUCK IN TEXTBOOKS, MIND BENDING QUANTUM EFFECTS ARE ABOUT TO POWER MAINSTREAM INNOVATION.

THE ECONOMIST (MARCH, 2017)

Message from the Chair of the Board

Momentum toward the development of a new large scale global industry based on transformative quantum technologies continues to grow and researchers at IQC continue to play a leadership role in advancing our fundamental knowledge of quantum information science and in developing new quantum technologies.

IQC recruits the very best researchers to Waterloo with a particular focus on the strongest younger talent. I want to welcome Christine Muschik and William Slofstra – new recruits to IQC in the past year. With 29 research faculty, IQC has been noted as the largest centre of its kind in the world.

I also want to recognize the important advances to our knowledge of quantum information by IQC researchers over the past year. Highlights include the following:

- Collaboration by **KEVIN RESCH**'s group with Perimeter Institute researchers led by **ROBERT SPEKKENS** to explore a new approach for learning about nature including testing quantum theory;
- Work by **RAYMOND LAFLAMME**, **JONATHAN BAUGH** and **BEI ZENG** toward improved quantum control by bootstrapping a 12 qubit quantum processor;
- *Physics World* recognized the work from **THOMAS JENNEWEIN** and **KEVIN RESCH**'s groups reporting the observation of three-photon interference as a 2017 physics breakthrough;
- **THOMAS JENNEWEIN**'s group also reported a successful airborne QKD test, a key step towards satellite deployment;
- **MICHAEL REIMER** reported in *Nature* on a new bright source of entangled photons based on nanowires; and
- **DMITRY PUSHIN** and **DAVID CORY**'s group demonstrated new control methods to prepare orbital angular momentum states of both neutrons and photons.

I am also excited by IQC's critical contribution to the growing number of new quantum technology start-ups in the Quantum Valley. For example, a quantum ESR technology start-up founded by an IQC researcher has developed technology that is literally 100,000 times more powerful and more sensitive than existing classical technologies. A quantum-safe encryption start-up in the Quantum Valley involving IQC researchers has developed a "quantum-safe" technology platform that will enable customers to protect their sensitive records from quantum computer attack with a software update. This start-up is also enabling Canada to play a leading role in the development of new global standards for quantum safe technologies.

In last year's report remarks, I noted the award to IQC of $76 million as part of the Canada First Research Excellence Fund. Matching funds from the University of Waterloo and industry partners including Quantum Valley Investments has resulted in IQC's $140 million Transformative Quantum Technologies (TQT) effort led by Professor David Cory. TQT will help IQC to continue to play a global leadership role in the development of a general-purpose quantum computer, quantum sensor technology, new quantum materials and quantum encryption technology.

I also want to note the important IQC effort led by Professor Thomas Jennewein in partnership with the Canadian Space Agency that is developing technology to enable the transfer of QKD encrypted data over long distances via satellites and thereby helping to solve a material limitation with QKD efforts around the world.

No discussion on IQC would be complete without an update on its general-purpose quantum computer efforts. Researchers at IQC are focused on the engineering of how to connect a large number of qubits like many other groups around the world. That said, what really sets IQC apart from other work around the world is IQC's extensive efforts to develop a quantum system that has less inherent noise. IQC researchers know that you can't build a useful quantum computer without tackling this fundamentally difficult issue and believe that their efforts to develop solutions in this regard upfront will have critical long-term benefits in their effort to develop a general-purpose quantum computer.

In the past year, IQC Founding Director Raymond Laflamme stepped down from this role after 15 years. His leadership and his many contributions as Founding Director helped establish IQC as one of a handful of quantum centres in the world. I want to personally thank Raymond for his leadership, his hard work and his invaluable contribution.

I am pleased that Raymond will continue to play a critical role at IQC as the holder of the *Mike and Ophelia Lazaridis John von Neumann Chair*. Raymond is a world leading expert in quantum error correction and his work in this regard will be a critical part of IQC's effort toward a quantum computer with less inherent noise. I am thrilled that Raymond has chosen to continue to play such an important role at IQC and am very pleased to have helped the University of Waterloo to make this happen.

IQC builds on top of the entrepreneurial culture that has led to the global recognition and success of the University of Waterloo. This unprecedented multidisciplinary 15 year university-wide effort to harness the power of quantum information science and quantum and nano materials technology will provide the University of Waterloo a unique and globally competitive advantage for decades to come.

Mike Lazaridis, O.C., O.Ont., FRS, FRSC
CHAIR,
IQC BOARD OF DIRECTORS

STRENGTHENING A GLOBAL QUANTUM INDUSTRY

Message from the Chair of the Executive Committee

The quest for the first quantum computer is a daunting aspiration. Yet it's an endeavour that I have no doubt will be accomplished at IQC.

As I look toward to the future, I'm reminded of the incredible growth and success that has already taken place here. It was passion, a bold vision, and the tremendous support of Mike Lazaridis that set the stage for IQC to emerge as a world leader in quantum information.

Combined with Raymond Laflamme's leadership, IQC has become known as one of the most advanced research facilities in the world — an epicentre of the next information revolution. As IQC celebrates its 15th anniversary, we also say goodbye to Raymond, marking another pivotal point in time in IQC's history.

At IQC, the biggest ideas are about what happens on the smallest of scales. As the University of Waterloo pursues the goal of becoming one of the most innovative universities in the world, we also welcome a new Vice-President, University Research, Charmaine Dean. Together, as we work towards achieving this substantial goal, there is no question that quantum research will play a significant role by strengthening a global quantum industry with deep societal impact.

George Dixon
CHAIR,
IQC EXECUTIVE COMMITTEE

Vice-President Academic & Provost, University of Waterloo

A Magnet FOR THE WORLD'S best

ATTRACTING THE LEADING MINDS IN QUANTUM INFORMATION SCIENCE AND TECHNOLOGY RESEARCH TO BUILD A HUB OF QUANTUM EXPERTISE.

ATTRACTING WORLD-CLASS RESEARCHERS

K. Rajibul Islam

K. RAJIBUL ISLAM joined IQC and the Department of Physics and Astronomy at the University of Waterloo from the MIT-Harvard Center for Ultracold Atoms (CUA). As a postdoctoral researcher at CUA, Islam studied entanglement in ultra-cold neutral bosonic atoms in optical potentials. He attended Quantum Innovators in 2015, and now leads the Laboratory for Quantum Information with Trapped Ions (QITI) at IQC. His research interests include quantum computation, experimental quantum many-body physics and the use of holography and high-resolution microscopy to manipulate many-body systems.

Crystal Senko

While completing her postdoctoral research at the MIT-Harvard CUA, **CRYSTAL SENKO** focused on the development of a photonic crystal waveguide for information transfer between atoms. During her fellowship in 2015, she attended Quantum Innovators and is now a member of IQC and the Department of Physics and Astronomy at the University of Waterloo. Senko explores how single atoms encoded with multiple levels of information, called qudits, can improve the efficiency of encoding information in quantum systems. Her work with trapped ions looks at the possibilities of building quantum systems, including spin chains with complicated behaviour that has yet to be demonstrated in a lab.

Jon Yard

From the Station Q team at Microsoft Research, **JON YARD** joined IQC as an Associate Professor in the Department of Combinatorics and Optimization in the Faculty of Mathematics and as an Associate Faculty member with the Perimeter Institute for Theoretical Physics (PI). Yard tackles complex mathematical problems in the areas of quantum information, quantum computing, algebraic number theory, quantum field theory and computational complexity theory. His research aims to understand the capabilities and limitations of devices for computing and distributing information.

FACULTY

2002

Raymond Laflamme
Physics and Astronomy

Hamed Majedi
2001-2014, now at the University of Waterloo

Michele Mosca
Combinatorics and Optimization

Ashwin Nayak
Combinatorics and Optimization

2004

Andris Ambainis
2004-2009, now at the University of Latvia

Richard Cleve
Cheriton School of Computer Science

2005

Gregor Weihs
2005-2010, now at the University of Innsbruck

Joseph Emerson
Applied Mathematics

Debbie Leung
Combinatorics and Optimization

2006

Norbert Lütkenhaus
Physics and Astronomy

Frank K. Wilhelm-Mauch
2006-2013, now at the Universität des Saarlandes

John Watrous
Cheriton School of Computer Science

Kevin Resch
Physics and Astronomy

2007

Andrew Childs
2007-2016, now at the University of Maryland

Jonathan Baugh
Chemistry

2008

Ben Reichardt
2008-2011, now at the University of Southern California

2009

Thomas Jennewein
Physics and Astronomy

Adrian Lupaşcu
Physics and Astronomy

2010

David Cory
Chemistry

Dmitry Pushin
Physics and Astronomy
Research Assistant Professor 2010-2017, now Assistant Professor, Physics and Astronomy

2011

Robert Koenig
2010-2015, now at Technische Universität München

Guo-Xing Miao
Electrical and Computer Engineering

2012

Matteo Mariantoni
Physics and Astronomy

Christopher Wilson
Electrical and Computer Engineering

2014

Michal Bajcsy
Electrical and Computer Engineering

Raffi Budakian
Physics and Astronomy

Kyung Soo Choi
Physics and Astronomy

2015

Michael Reimer
Electrical and Computer Engineering

Vern Paulsen
Pure Mathematics

2016

William Slofstra
Pure Mathematics
Research Assistant Professor 2015-2017, now Assistant Professor, Pure Mathematics

Wei Tsen
Chemistry

Na Young Kim
Electrical and Computer Engineering

Jon Yard
Combinatorics and Optimization

K. Rajibul Islam
Physics and Astronomy

Crystal Senko
Physics and Astronomy

2017

Christine Muschik
Physics and Astronomy

Research at IQC is fundamentally interdisciplinary, spanning theory and experiment, to pursue every avenue of quantum information science. IQC fosters collaboration across disciplines and across borders.

Our researchers are appointed to both IQC and one of seven departments across three faculties at the University of Waterloo:

FACULTY OF MATHEMATICS

- Applied Mathematics
- Combinatorics and Optimization
- Computer Science
- Pure Mathematics

FACULTY OF SCIENCE

- Chemistry
- Physics and Astronomy

FACULTY OF ENGINEERING

- Electrical and Computer Engineering

IQC Research Groups

Coherent Spintronics Group
Jonathan Baugh

Engineered Quantum Systems Lab
Christopher Wilson

Functional Quantum Materials
Guo-Xing Miao

Laboratory for Digital Quantum Matter
Matteo Mariantoni

Laboratory of Ultracold Quantum Matter and Light
Kyung Soo Choi

Laboratory for Quantum Information with Trapped Ions
K. Rajibul Islam

Mathematics of Quantum Information
William Slofstra

Nano-Photonics and Quantum Optics Lab
Michal Bajcsy

Nanoscale Magnetic Resonance Imaging Lab
Raffi Budakian

Quantum Error Control and Error Correction
Raymond Laflamme

Optical Quantum Communication Theory Group
Norbert Lütkenhaus

Quantum Innovation (QuIN) Lab
Na Young Kim

Quantum Information and Computation Theory Group
Richard Cleve
Joseph Emerson
Raymond Laflamme
Debbie Leung
Michele Mosca
Ashwin Nayak
Vern Paulsen
John Watrous
Jon Yard

Quantum Materials and Devices Lab
Wei Tsen

Quantum Optics and Quantum Information Lab
Kevin Resch

Quantum Optics Theory
Christine Muschik

Quantum Photonic Devices Lab
Michael Reimer

Quantum Photonics Lab
Thomas Jennewein

Quantum Processors Lab
David Cory

Quantum-safe Cryptography Group
Michele Mosca

Quantum Sensing in Physics
Dmitry Pushin

Quantum Software Group
Michele Mosca

Superconducting Quantum Devices Group
Adrian Lupaşcu

Trapped Ion Quantum Control
Crystal Senko

Powered BY *people*

A COLLABORATIVE APPROACH WITH GLOBAL REACH

COLLABORATION IS A CATALYST FOR DISCOVERY. IQC RESEARCHERS WORK CLOSELY WITH PEERS FROM AROUND THE GLOBE. IQC'S INTERNATIONAL NETWORK CONTINUES TO EXPAND, MAKING CONNECTIONS AND PARTNERSHIPS THAT LAY THE GROUNDWORK FOR EXCITING FUTURE DEVELOPMENTS.

Agreements & Exchanges

NATIONAL & INTERNATIONAL AGREEMENTS

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

QUEBEC

- Institut national de la recherche scientifique
- Institut Transdisciplinaire d'Information Quantique

CHINA

- Tsinghua University
- University of Science and Technology of China

INDIA

- Raman Research Institute

ISRAEL

- Technion — Israel Institute of Technology

KOREA

- Korea Institute of Science and Technology

THE NETHERLANDS

- Delft University of 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
- Université Paris Diderot

GERMANY

- Friedrich-Alexander-Universität Erlangen-Nürnberg

LATVIA

- University of Latvia

THE NETHERLANDS

- Delft University of Technology

SINGAPORE

- National University of Singapore

IN 2017, IQC RESEARCHERS:

PARTICIPATED IN **329 research collaborations spanning 34 countries and 180+ institutions.**

WELCOMED **159 scientific visitors from 129 leading institutions to exchange ideas and research in quantum information.**

70%+
of co-authored papers are with international collaborators

Computing quantum condensed matter

AFFILIATE PROFILE

Theoretical researcher ROGER MELKO studies the big questions of quantum condensed-matter physics using computational methods such as Monte Carlo simulations. He won the Canadian Association of Physicists (CAP) Herzberg Medal in 2016 for his outstanding early-career achievements in condensed matter physics, and currently holds a Canada Research Chair in Computational Quantum Many-Body Physics.

As an IQC affiliate and Associate Professor in the University of Waterloo's Department of Physics and Astronomy, Melko supervises postdoctoral fellow **HILARY CARTERET** and collaborates with other IQC researchers, including postdoctoral fellow **CHRIS HERDMAN** and fellow affiliate **PIERRE-NICHOLAS ROY**.

After an artificial intelligence program created by Google defeated world champion Lee Sedol in Go, a game magnitudes more complex than chess, Melko began to think about how machine learning and artificial intelligence could help solve the grand problems of physics — especially if implemented on a quantum computer. In August 2016, Melko organized a conference at the Perimeter Institute for Theoretical Physics that aimed to explore the potential of machine learning in quantum research.

"For now, machine minds can be great at chess and even Go, but these are just the beginnings of a much larger revolution. What we're seeing now shows that machine learning has the power to advance science, technology, and society in profound ways," said Melko.

ACADEMIC & SCIENTIFIC VISITORS

INCLUDING:

Leena Aggarwal,
Indian Institute of Science Education and Research

David Allcock,
National Institute of Standards and Technology

José Aumentado,
National Institute of Standards and Technology

Valentina Baccetti,
Macquarie University

Shalev Ben-David,
Massachusetts Institute of Technology

Gaurav Bhole,
The University of Queensland

Nina Bindel,
Technische Universität Darmstadt

Justin Bohnet,
National Institute of Standards and Technology

Brendan Bramman,
Hastings College

Michael Bremner,
University of Technology Sydney

Harry Buhrman,
University of Amsterdam

Alexei Bylinskii,
Massachusetts Institute of Technology

Hugo Cable,
University of Bristol

Andrew Cameron,
University of Prince Edward Island

Nai-Hui Chia,
Pennsylvania State University

Hong Chiang,
Chongqing University

Joseph Choi,
University of Rochester

Yonuk Chong,
Korea Research Institute of Standards and Science

Charles W. Clark,
National Institute of Standards and Technology

Milena Crnogorcevic,
Middlebury College

Animesh Datta,
The University of Warwick

Andy Ding,
Illinois Wesleyan University

Juan Carlos García-Escartín,
Universidad de Valladolid

Lino Eugene,
McGill University

Dennis Feng,
University of California, Berkeley

Andreas Fognini,
Delft University of Technology

Luis Garay,
Universidad Complutense de Madrid

Laura García-Álvarez,
University of the Basque Country

Miriam Gauntlett,
University of Cambridge

Peter Geltenbort,
Institut Laue-Langevin

Zhexuan Gong,
University of Maryland, College Park

Stephen K. Gray,
Argonne National Laboratory

Milena Grifoni,
Universität Regensburg

Simon Gröblacher,
Delft University of Technology

Jason Herrmann,
Harvard University

Matt Hodel,
Massachusetts Institute of Technology

Rolf Horn,
Quspin Technologies Inc.

Sara Hosseini,
Australian National University

Onur Hosten,
Stanford University

Shilling Huang,
Tsinghua University

Bruno Huttner,
ID Quantique

K. Rajibul Islam,
MIT-Harvard Center for Ultracold Atoms

Youn-Chang Jeong,
Agency for Defense Development

Robert Johnson,
Pennsylvania State University

Noah Dylan Johnson,
University of Wisconsin-Madison

Peter Johnson,
Dartmouth College

Amir Karamlou,
Massachusetts Institute of Technology

Angela Karanjai,
The University of Sydney

Torsten Karzig,
Microsoft Research, Station Q

Thomas Kauten,
University of Innsbruck

Imran Khan,
Max Planck Institute for the Science of Light

Cheol-Joo Kim,
Cornell University

Yoon-Ho Kim,
Pohang University of Science and Technology

Marcelo Knobel,
Universidade Estadual de Campinas (Unicamp)

Mike Kobierski,
McGill University

Natsumi Komatsu,
Rice University

Pravesh Kothari,
Princeton University

Sophie Laplante,
Université Paris Diderot

Jean Lapointe,
National Research Council

Rébecca Lapointe,
Université de Montréal

Dariusz Lasecki,
Adam Mickiewicz University

Mathieu Laurière,
New York University, Shanghai

Youn Seok Lee,
Pusan National University

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

Yiruo Lin,
University of Illinois at Urbana-Champaign

Alexander Ling,
Centre for Quantum Technologies

Rotem Liss,
Technion — Israel Institute of Technology

Zidu Liu,
University of Science and Technology of China

Jorma Louko,
The University of Nottingham

Shunlong Luo,
Academy of Mathematics and Systems Science, Chinese Academy of Sciences

Michael Lynch,
Acadia University

Xionfeng Ma,
Tsinghua University

Xiaodong Ma,
University of Science and Technology of China

Arpita Maitra,
Indian Institute of Management Calcutta

Laura Mancinska,
University of Bristol

Jacob Marks,
Yale University

Christoph Marquardt,
Max Planck Institute for the Science of Light

Mark McArdle,
eSentire Inc.

Akihiro Mizutani,
Osaka University

Christopher Monroe,
University of Maryland, College Park

Tal Mor,
Technion — Israel Institute of Technology

Bhaskaran Muralidharan,
Indian Institute of Technology Bombay

Daniela Angulo Murcillo,
National University of Colombia

Christine Muschik,
University of Innsbruck

Robert Myers,
Perimeter Institute

Bienvenu Ndagano,
University of the Witwatersrand

William Oliver,
Massachusetts Institute of Technology

Jonathan Oppenheim,
University College London

Zachary Pagel,
Tufts University

Haining Pan,
Nanjing University

Serge-Olivier Paquette,
Université de Montréal

Apoorva D. Patel,
Centre for High Energy Physics, Indian Institute of Science

Atmn Patel,
Kingsville District High School

Evan Peters,
Oregon State University

Marco Piani,
University of Strathclyde

Todd Pittman,
University of Maryland

Dominique Pouliot,
University of Illinois at Urbana-Champaign

Lorenzo M. Procopio,
University of Vienna

Christian Prosko,
University of Alberta

Fereshteh Rajabi,
Western University

C. Jess Riedel,
Perimeter Institute

Ivana Rilak,
University of Belgrade

William Rose,
University of Illinois at Urbana-Champaign

Mahrud Sayrafi,
University of California, Berkeley

Volkher Scholz,
Ghent University

Sacha Schwarz,
Universität Bern

Karolina Sedziak,
Nicolaus Copernicus University

Crystal Senko,
Harvard University

Francois Sfigakis,
University of Cambridge

Nachiket Sherlekar,
University of Waterloo

Heedeuk Shin,
Pohang University of Science and Technology

Carlos Silva,
Université de Montréal

Stephanie Simmons,
Simon Fraser University

Urbasi Sinha,
Raman Research Institute

Sam Slezak,
Humboldt State University

Tom Stace,
The University of Queensland

Douglas Stebila,
McMaster University

Martin Suchara,
AT&T Labs Research

Shihai Sun,
National University of Defence Technology

Matthew Taylor,
Dalhousie University

Rakesh Tiwari,
McGill University

Bill Unruh,
University of British Columbia

Mehran Vahdani,
University of British Columbia

Henry De Valence,
Eindhoven University of Technology

Juan Bermejo-Vega,
Perimeter Institute

Michael Walter,
Stanford University

Yidun Wan,
Fudan University

Dongsheng Wang,
University of Calgary

Hengyan Wang,
University of Science and Technology of China

Tzu-Chieh Wei,
University of British Columbia

Ryan Wilson,
College of New Jersey

Hugo Woerdeman,
Drexel University

Michael Wolfe,
University of Maryland

Franco N.C. Wong,
Massachusetts Institute of Technology

Bowen Yang,
Nankai University

Penghui Yao,
University of Maryland, Baltimore County

Beni Yoshida,
Perimeter Institute

Dapeng Yu,
South University of Science and Technology of China

Henry Yuen,
University of California, Berkeley

Man-Hong Yung,
South University of Science and Technology of China

Liuyan Zhao,
University of Michigan

Yu Zheng,
Nankai University

Xiaobo Zhu,
University of Science and Technology of China

Karol Życzkowski,
Jagiellonian University

LONG-TERM VISITORS

INCLUDING:

Daniela Angulo Murcillo,
National University of Colombia

Valentina Baccetti,
Macquarie University

Gaurav Bhole,
The University of Queensland

Milena Crnogorcevic,
Middlebury College

Noah Dylan Johnson,
University of Wisconsin-Madison

Dennis Feng,
University of California, Berkeley

Andreas Fognini,
Delft University of Technology

Jason Herrmann,
Harvard University

Matt Hodel,
Massachusetts Institute of Technology

Shilling Huang,
Tsinghua University

Bienvenu Ndagano,
University of the Witwatersrand

Robert Johnson,
Pennsylvania State University

Amir Karamlou,
Massachusetts Institute of Technology

Angela Karanjai,
The University of Sydney

Thomas Kauten,
University of Innsbruck

Natsumi Komatsu,
Rice University

Rébecca Lapointe,
Université de Montréal

Dariusz Lasecki,
Adam Mickiewicz University

Yoon Seok Lee,
Pusan National University

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

Yiruo Lin,
University of Illinois at Urbana-Champaign

Zidu Liu,
University of Science and Technology

Shunlong Luo,
Academy of Mathematics and Systems Science, Chinese Academy of Sciences

Xiaodong Ma,
University of Science and Technology of China

Arpita Maitra,
Indian Institue of Management Calcutta

Jacob Marks,
Yale University

Akihiro Mizutani,
Osaka University

Zachary Pagel,
Tufts University

Haining Pan,
Nanjing University

Serge-Olivier Paquette,
Université de Montréal

Apoorva Patel,
Centre for High Energy Physics, Indian Institute of Science

Atmn Patel,
Kingsville District High School

Dominique Pouliot,
University of Illinois at Urbana-Champaign

K. Rajibul Islam,
MIT-Harvard Center for Ultracold Atoms

Ivana Rilak,
University of Belgrade

Mahrud Sayrafi,
University of California, Berkeley

Karolina Sedziak,
Nicolaus Copernicus University

Francois Sfigakis,
University of Cambridge

Nachiket Sherlekar,
University of Waterloo

Martin Suchara,
AT&T Labs Research

Yidun Wan,
Fudan University

Hengyan Wang,
University of Science and Technology of China

Hugo Woerdeman,
Drexel University

Michael Wolfe,
University of Maryland

Bowen Yang,
Nankai University

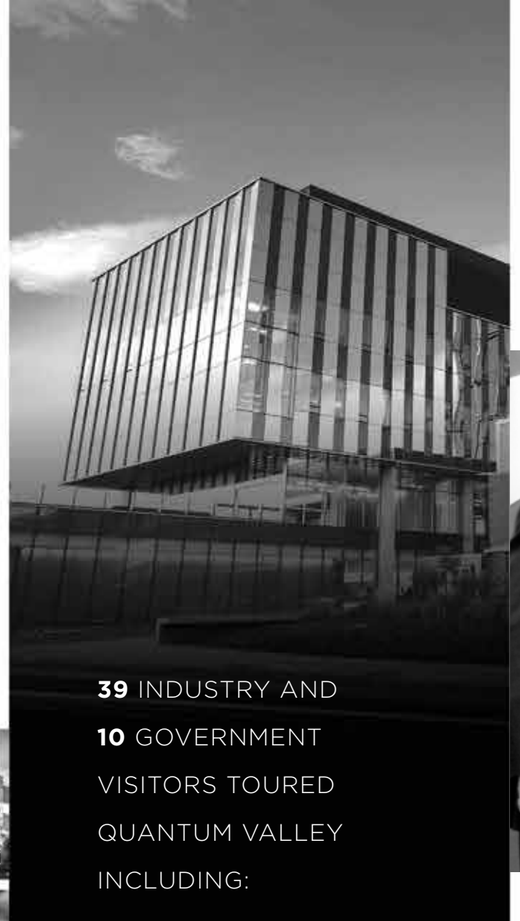
Yu Zheng,
Nankai University

TOURING QUANTUM VALLEY

Canada Leads By Example In Quantum Research

The world looks to Canada for insight in quantum research. Throughout the year, we welcome researchers, industry and government from all over the world to share quantum research and build partnerships.

President of Croatia, **KOLINDA GRABAR-KITAROVIĆ**, tours the Quantum Optics and Quantum Information Lab during a visit to IQC.



39 INDUSTRY AND **10** GOVERNMENT VISITORS TOURED QUANTUM VALLEY INCLUDING:

- Taiwan Ministry of Science Delegation
- Delegation of **EU** Flagship officials
- Embassy of France, **BRIGITTE PROUCELLE** and **ANTOINE RAUZY**
- Norway's Ambassador to Canada, **ANNE KARI HANSEN OVIND**
- President of Croatia, **KOLINDA GRABAR-KITAROVIĆ**

TQT Transformative Quantum Technologies

Vice-President Academic & Provost, University of Waterloo **GEORGE DIXON**, Founder and Managing Partner, Quantum Valley Investments **MIKE LAZARIDIS**, Canada Excellence Research Chair Laureate **DAVID CORY,** Minister of Science, the Honourable **KIRSTY DUNCAN**, President and Vice-Chancellor, University of Waterloo **FERIDUN HAMDULLAHPUR**, founding Executive Director **RAYMOND LAFLAMME**, Executive Vice-President, Social Sciences and Humanities Research Council **BRENT HERBERT-COPLEY**

Transformative Quantum Technologies

Continually pushing the boundaries of quantum research leads to new theoretical perspectives, proposed experiments and practical technologies. A new initiative established last fall with support from the Canada First Research Excellence Fund (CFREF) continues to push boundaries.

The Transformative Quantum Technologies (TQT) program tackles three grand challenges in quantum research: the development of a universal quantum processor, impactful quantum sensors and long-distance quantum communication. Under the direction of **DAVID CORY**, Canada Excellence Research Chair in Quantum Information Processing, TQT aims to connect academic research with industry applications in a variety of fields, and to continue paving the way for transformative quantum technologies.

"Quantum mechanics enable devices that are otherwise impossible in the classical world, and these revolutionary devices will transform the way we interact with and learn about the world. Transformative Quantum Technologies aims to develop new quantum technologies and to connect quantum devices to applications spanning the fields of medicine, health, navigation, environment, materials and others."

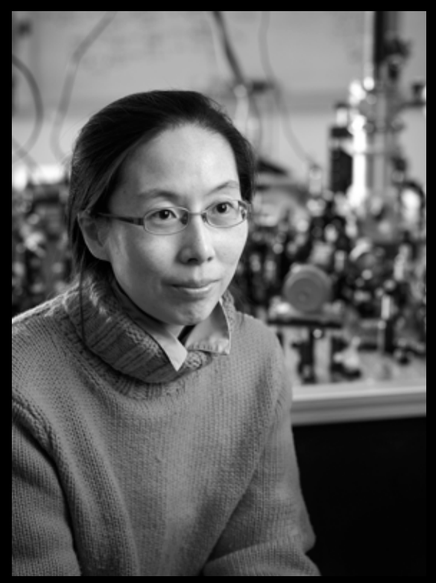
DAVID CORY,
Canada Excellence Research Chair, Laureate

World-class RESEARCH

FROM THEORY TO EXPERIMENT, THE BREADTH AND QUALITY OF IQC'S RESEARCH INFRASTRUCTURE ALLOWS QUANTUM INFORMATION SCIENCE AND TECHNOLOGY ADVANCEMENT AT THE HIGHEST INTERNATIONAL LEVEL.

THROW OUT THE RULE BOOK, IT'S QUANTUM.

EXPERIMENTAL RESEARCH IN THE LAB DOESN'T ALWAYS LEAD TO QUICK RESULTS.



EXPLORE A ROAD THAT HASN'T BEEN TRAVELLED ON BEFORE.

PAVING THE WAY TOWARDS THE REALIZATION OF A UNIVERSAL QUANTUM COMPUTER, QUBIT BY QUBIT.

A PASSION FOR discovery

NA YOUNG KIM took the road less travelled. She spent almost two years working on product development for Apple Inc., but her passion for discovery led her back to academia. Kim returned to research at IQC in 2016. She heads the Quantum Innovation (QuIN) laboratory, which aims to build large-scale quantum processors based on novel materials and advanced technologies.

Currently, Kim and her team are on track to develop semiconductor-based quantum machines. “Machine is a general term,” noted Kim. “A quantum machine could be a device, system, or architecture. The details are in the discovery.”

Key materials

Kim is taking a ground-up approach and starting with materials. Historically, stone, iron and other metals have played a significant role in developing technology. Kim believes that materials will once again be revolutionary in the quantum age.

Materials development is a new area for trained physicist Kim. And she’s boldly expanded her understanding of materials science, chemistry and engineering to steer her research forward. In fact, she’s also an Associate Professor in the University of Waterloo’s Department of Electrical and Computer Engineering.

Superior solid-state circuits

Kim and the QuIN team are designing an integrated solid-state circuit with superior optical, mechanical and thermal performance compared to current technology. Thanks to quantum physics, the enhanced capability of the circuit could play a key role in bridging quantum and classical technology. “A quantum computer likely won’t replace the classical computers we use today, but will serve complementary purposes,” said Kim.

Classical and quantum technologies may work together to solve problems. A quantum simulator could be engineered to address issues in condensed matter physics. Or to simulate chemical reactions, such as molecule bonding for the design and delivery of medical drugs.

New perspectives

Kim takes a holistic approach to research. She plans her research route carefully, but knows it’s important to stay open-minded about the direction it takes. “Research and discovery is a cycle. The best engineering will provide new perspectives for exploring the fundamental aspects of quantum information science.”

Science and technology will emerge together and propel quantum information research forward on the adventurous path to discovery.

ON THE path TO BUILDING A *quantum* computer

On a quiet morning at the Research Advancement Centre (RAC) building, a steady hum and chirp drifts down the hallway. The repetitive, calming whir signals the ongoing, crucial work of the dilution refrigerator keeping the tiny device inside cooled and in the desired quantum state.

Principal investigator **JONATHAN BAUGH** walks the hall to the dilution refrigerator in the Coherent Spintronics lab daily. There, he and his students experiment with nanoscale electronic devices at low temperatures to learn more about quantum physics. According to Baugh, “Understanding more about how to control physics at the nanoscale gives us a powerful toolbox to work with.”

It’s a toolbox that Baugh’s been developing for 15 years. He started his journey at IQC as one of the very first postdoctoral fellows in 2002. His supervisor, **RAYMOND LAFLAMME**, introduced him to the field of quantum information. Now Baugh’s research group focuses on applying quantum control methods to single quantum systems with potential to scale up, like the spin of a single electron trapped in a quantum dot (also known as an artificial atom). The quantum dots studied in Baugh’s lab are made from semiconductors and are around 50 nanometers in size.

Control at scale

Gaining the ability to control quantum states at the level of one or two electrons is the first step in a larger, more ambitious endeavour. The ultimate goal is to put the pieces in place to build a large scale quantum information-processing device — the inner workings of a quantum computer. “That would have a huge impact and could change the world,” said Baugh. “Theoretically we can model the behaviour of these quantum systems. Until we actually make and study them in a lab, we won’t know what all the real challenges to scaling up will be.”

A glimpse into the future

Experimental research in the lab doesn’t always lead to quick results. But it does give us a glimpse into future applications for quantum technologies. “Sometimes there are big breakthroughs, but equally important are the incremental steps in getting to the final goal,” said Baugh.

One example is the quantum memristor — a resistor with memory — the result of Baugh’s collaboration with colleagues at Oxford University. The quantum memristor regulates the flow of electrical current using a pair of quantum dots. Neuroscientists predict that memristive-type components could be important for the study of brain function. In concept, the quantum memristor may be used to build artificial circuits to simulate the way the brain works.

In the lab, the constant hum and chirp of the dilution refrigerator is a reminder of steady steps forward. Advancing technology is catching up with theory, like the nanoscale devices in Baugh’s lab. The path to building a quantum computer is in sight.

Curiosity
DRIVES **INNOVATION**

RAYMOND LAFLAMME:
A *path* OF *curiosity*

Quantum technologies, like all innovations, were born out of the innate sense of curiosity that drives us. We are curious about the things around us. We learn about something — how it behaves, how it works. Then we capture that behaviour, harness it to do something for society and start the cycle all over again.

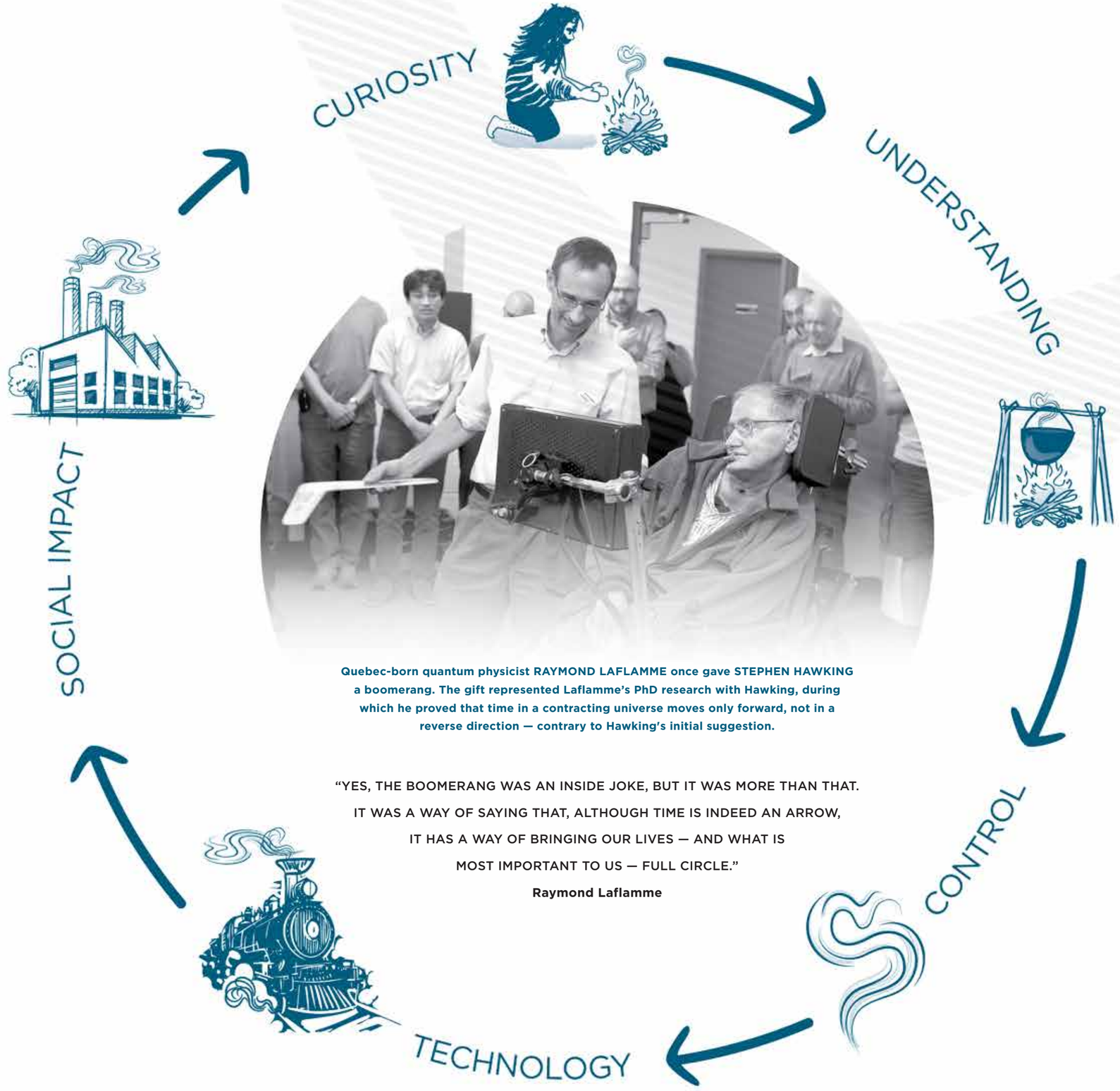
From a young age, **RAYMOND LAFLAMME**'s innate sense of curiosity led him down the path of discovery. He asked his grandfather how airplanes flew and learned how to repair lawnmowers from his mother.

His curious nature eventually steered him towards a career in research. Laflamme earned his PhD under the supervision of **STEPHEN HAWKING**, focusing on general relativity and quantum cosmology.

After completing a Killam postdoctoral fellowship at the University of British Columbia, Laflamme began exploring quantum computing as an Oppenheimer Fellow at Los Alamos National Laboratory in New Mexico. There, he developed quantum-error correction theory and performed the first experimental demonstration of quantum-error correction.

His curiosity piqued when **MIKE LAZARIDIS** and **HOWARD BURTON** travelled to meet with him in **DAVID CORY**'s lab at the Massachusetts Institute of Technology. Lazaridis had a vision — to start an institute for quantum computing at the University of Waterloo, and he wanted Laflamme to lead it. Laflamme said to him: "If you're really interested in quantum information, you should not focus only on the theoretical side — there should be a strong experimental piece too. And it should be multidisciplinary, bringing mathematicians, computer scientists, chemists and engineers together."

As Laflamme put it, "I took a leap of faith into what has become the most exciting work of my life." He moved to Waterloo and the Institute for Quantum Computing (IQC) was born. In 15 years serving as Executive Director, Laflamme's leadership established IQC as a world-class research hub, positioning Canada at the forefront of the quantum revolution. Now, curiosity pulls Laflamme back into the world of research to start the cycle all over again.



Quebec-born quantum physicist RAYMOND LAFLAMME once gave STEPHEN HAWKING a boomerang. The gift represented Laflamme's PhD research with Hawking, during which he proved that time in a contracting universe moves only forward, not in a reverse direction — contrary to Hawking's initial suggestion.

"YES, THE BOOMERANG WAS AN INSIDE JOKE, BUT IT WAS MORE THAN THAT. IT WAS A WAY OF SAYING THAT, ALTHOUGH TIME IS INDEED AN ARROW, IT HAS A WAY OF BRINGING OUR LIVES — AND WHAT IS MOST IMPORTANT TO US — FULL CIRCLE."

Raymond Laflamme

“CURIOSITY IS A DRIVING FORCE OF INNOVATION. OUR DESIRE TO UNDERSTAND HOW THE WORLD AROUND US OPERATES LEADS US TO THE NEED TO CONTROL THAT WORLD AND CREATE TECHNOLOGIES TO BENEFIT SOCIETY.”

THE PATH TO QUANTUM VALLEY

Message from the Executive Director

Fifteen years ago, I set out on an unknown path. Guided by visionary Mike Lazaridis, IQC was created to foster pioneering research into the next technological revolution — the quantum revolution. Today, IQC stands among the top quantum research institutes internationally.

When I look back on the path that led to the growth of IQC today, I see the collective efforts and extraordinary accomplishments of a vibrant scientific community. Our faculty members, postdoctoral fellows, students, associates and affiliates are advancing the field of quantum research, making discoveries and building on Waterloo’s reputation of research excellence. Theoretical concepts and transformational technologies are moving from the lab to the marketplace, poised to make societal impacts.

I thank the continued support of our partners who have lined the path — Mike and Ophelia Lazaridis, Doug Fregin, the University of Waterloo and both the provincial and federal governments — enabling IQC to adapt to and shape the ever-changing research landscape at a global scale. IQC plays a critical role in building the Quantum Valley, together with the Perimeter Institute of Theoretical Physics, Quantum Valley Investments and the Lazaridis School at Wilfrid Laurier University. I also want to thank the staff at IQC and colleagues throughout the University and abroad for their profound contribution to build IQC.

We have come so far in 15 years, yet there is still a long way to go. When I look ahead to see what the future path holds, I see tremendous opportunities to explore: new areas of research, exciting collaborations and impactful advancements. In the coming year, a new Director will also set a path forward for IQC that will continue to shape and influence our quantum research agenda nationally and internationally.

Thank you to all who join and support IQC on this exhilarating journey. Together, we will lead the quantum technology industry.

Raymond Laflamme
FOUNDING EXECUTIVE DIRECTOR

Institute for Quantum Computing, University of Waterloo

15 years

OF QUANTUM RESEARCH AND DISCOVERY AT IQC

November
1st EXPERIMENTAL REALIZATION OF HEAT-BATH ALGORITHMIC COOLING IN A SOLID-STATE NUCLEAR SPIN SYSTEM BY **JONATHAN BAUGH**, **ASHWIN NAYAK**, **RAYMOND LAFLAMME** AND OTHERS

May
$12.5M
PLEDGE BY **MIKE AND OPHELIA LAZARIDIS** FOR THE MIKE & OPHELIA LAZARIDIS QUANTUM-NANO CENTRE

02

November
OFFICIAL OPENING IN THE PHYSICS BUILDING

December
$3M PLEDGE BY **MIKE AND OPHELIA LAZARIDIS** WITH MATCHING CONTRIBUTIONS FROM CFI AND THE ONTARIO INNOVATION TRUST

03

April
$30M DONATION BY **MIKE AND OPHELIA LAZARIDIS** TO SECURE FURTHER FUNDING TOTALLING $100 MILLION

04

September
INVITATION TO LOCAL HIGH SCHOOL STUDENTS TO TOUR LABS, LAUNCHING OUTREACH EFFORTS

May
IQC MOVES INTO B.F. GOODRICH BUILDING

November
1st PHD GRADUATE: **DAVID POULIN**

05

May
DAVID CORY, **RAYMOND LAFLAMME** AND OTHERS SET LONGSTANDING WORLD RECORD FOR UNIVERSAL CONTROL OF LARGEST NUMBER OF QUBITS (12)

06

March
$50M
PLEDGE BY GOVERNMENT OF ONTARIO TO SUPPORT EXCELLENCE IN GLOBAL RESEARCH

May
$49M
COMMITMENT FROM CFI, ONTARIO RESEARCH FUND AND UNIVERSITY OF WATERLOO TO CONSTRUCT THE LAZARIDIS QUANTUM-NANO CENTRE

July
MICHELE MOSCA AND OTHERS SHOW SELF-TESTING OF QUANTUM CIRCUITS

07

January
PHILLIP KAYE, **RAYMOND LAFLAMME** AND **MICHELE MOSCA** PUBLISH RESPECTED TEXTBOOK *AN INTRODUCTION TO QUANTUM COMPUTING*

February
$50M
DONATED BY **MIKE AND OPHELIA LAZARIDIS**, MATCHED BY BOTH THE GOVERNMENT OF ONTARIO AND INDUSTRY CANADA

May
IQC AND PERIMETER INSTITUTE COLLABORATE FOR MONTH-LONG CONFERENCE, "TAMING THE QUANTUM WORLD"

April
EXPANSION INTO RESEARCH ADVANCEMENT CENTRE I (RAC I)

08

09

August
1st QUANTUM **CRYPTOGRAPHY SCHOOL FOR YOUNG STUDENTS** (QCSYS)

April
$50M
COMMITTED BY GOVERNMENT OF CANADA TO BUILD, PURCHASE AND RECRUIT HIGHLY QUALIFIED PERSONNEL

May
ANDREW CHILDS DEMONSTRATES THE FEASIBILITY OF UNIVERSAL COMPUTATION USING QUANTUM WALKS

June
1st **UNDERGRADUATE SCHOOL ON EXPERIMENTAL QUANTUM INFORMATION PROCESSING** (USEQIP)

August
JOHN WATROUS AND COLLABORATORS RESOLVE LONGSTANDING OPEN QUESTION ABOUT COMPLEXITY THEORY: QIP=PSPACE

10

January
PRELIMINARY TECHNOLOGY FEASIBILITY STUDY IN PARTNERSHIP WITH DEFENSE RESEARCH AND DEVELOPMENT CANADA (DRDC) MARKS THE LAUNCH OF THE QUANTUM ENCRYPTION AND SCIENCE SATELLITE (QEYSSAT) PROJECT

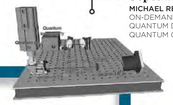
September
UNIVERSITY OF WATERLOO AND IQC LAUNCH THE COLLABORATIVE **QUANTUM INFORMATION GRADUATE PROGRAM**

March
RICHARD CLEVE AND COLLABORATORS DEMONSTRATE THAT QUANTUM MECHANICS CAN BE USED TO OBTAIN DRAMATIC ADVANTAGES FOR COMMUNICATION COMPLEXITY

June
IQC EXPANDS INTO RESEARCH ADVANCEMENT CENTRE II (RAC II), FUNDED BY **MIKE LAZARIDIS** AND **DOUG FREGIN**

June
DEBBIE LEUNG AND COLLABORATORS SHOW THAT ENTANGLED STATES CAN BE USED TO INCREASE THE NUMBER OF ERRORLESS CLASSICAL MESSAGES

June
CONTEXTUALITY SHOWN AS A NECESSARY RESOURCE FOR ACHIEVING THE ADVANTAGES OF QUANTUM COMPUTATION BY **JOSEPH EMERSON** AND TEAM

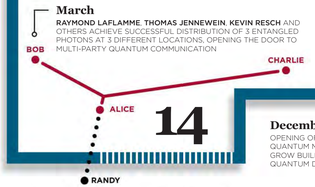


September
MICHAEL REIMER AND OTHERS DEVELOP 1st SOURCE OF ON-DEMAND TIME-BIN ENTANGLED PHOTON PAIRS USING QUANTUM DOTS, WHICH COULD INCREASE SECURITY IN QUANTUM COMMUNICATION

September
RAFFI BUDAKIAN BUILDS ULTRA-SENSITIVE DETECTION INSTRUMENTS THAT LOOK AT NATURE IN FUNDAMENTALLY NEW WAYS

July
$25M FUNDING OVER 5 YEARS RENEWED FROM PROVINCE OF ONTARIO

March
RAYMOND LAFLAMME, **THOMAS JENNEWEIN**, **KEVIN RESCH** AND OTHERS ACHIEVE SUCCESSFUL DISTRIBUTION OF 3 ENTANGLED PHOTONS AT 3 DIFFERENT LOCATIONS, OPENING THE DOOR TO MULTI-PARTY QUANTUM COMMUNICATION



14

December
OPENING OF A NEW QUANTUM MATERIALS LAB TO GROW BUILDING BLOCKS OF QUANTUM DEVICES

July
MIT TECHNOLOGY REVIEW NAMES IQC AS A PILLAR FOR BUILDING A QUANTUM INDUSTRY IN WATERLOO

May
GUO-XING MIAO, **DAVID CORY** AND OTHERS DEVELOP A SPECTROSCOPIC TOOL FOR CHEMISTRY AND MATERIALS SCIENCE OF THIN FILMS, USEFUL IN DESIGNING A QUANTUM INFORMATION PROCESSOR

13

September
GRAND OPENING OF THE **MIKE AND OPHELIA LAZARIDIS QUANTUM-NANO CENTRE**

August
IQC STARTUP **UNIVERSAL QUANTUM DEVICES, INC.** SELLS ITS 1st MULTI-PURPOSE TOOL FOR QUANTUM OPTICS RESEARCH

12

July
POSTDOC **ANNE BROADBENT** CO-ORGANIZES 1st ANNUAL WOMEN IN PHYSICS CANADA CONFERENCE WITH PERIMETER INSTITUTE

December
DMITRY PUSHIN AND **DAVID CORY** APPLY QUANTUM INFORMATION TECHNIQUES FOR THE 1st TIME TO NEUTRON INTERFEROMETRY, ALLOWING FOR SMALLER, FASTER, MORE RESILIENT SENSORS

11

January
EVOLUTIONQ INC., A STARTUP SPECIALIZING IN QUANTUM-RISK MANAGEMENT STRATEGIES AND ROBUST CYBERSECURITY TOOLS, IS FOUNDED BY **MICHELE MOSCA** AND **NORBERT LÜTKENHAUS**

October
UNIVERSITY OF WATERLOO STUDENT CHAPTER OF THE OPTICAL SOCIETY (OSA) OPEN *LIGHT: ILLUMINATED*

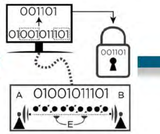
November
COLLABORATIVE RESEARCH BY **KYUNG SOO CHOI** OPENS A ROUTE TOWARDS DISSIPATIVE PREPARATION OF MANY-BODY ENTANGLEMENT WITH UNPRECEDENTED SCALING BEHAVIOUR

December
1st **SCHRÖDINGER'S CLASS** FOR SCIENCE EDUCATORS

Schrödinger's Class

15

May
DEVELOPMENT OF THE FIRST AVAILABLE SOFTWARE TO EVALUATE THE SECURITY OF ANY PROTOCOL FOR QUANTUM KEY DISTRIBUTION (QKD) BY **NORBERT LÜTKENHAUS** GROUP



April
VERN PAULSEN CO-PUBLISHES THE TEXTBOOK *AN INTRODUCTION TO THE THEORY OF REPRODUCING KERNEL HILBERT SPACES*

16

June
WILLIAM SLOFTSRA LEADS THE DISCOVERY OF THE SOLUTION TO THE LONGSTANDING TSIRELSON'S PROBLEM, WHICH HELPS MATHEMATICIANS UNDERSTAND THE POSSIBLE WAYS IN WHICH TWO SPATIALLY SEPARATED SYSTEMS BEHAVE

TQT Transformative Quantum Technologies

September
IQC LEADS CANADA FIRST RESEARCH EXCELLENCE FUND INITIATIVE AT WATERLOO, INCLUDING THE **TRANSFORMATIVE QUANTUM TECHNOLOGIES** PROGRAM

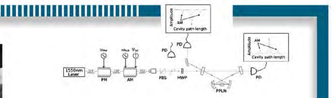
October
EXPERIMENT BY **ADRIAN LUPASCU**, **CHRIS WILSON** AND OTHERS ACHIEVES THE STRONGEST COUPLING BETWEEN LIGHT AND MATTER EVER RECORDED

October
QUANTUM: THE EXHIBITION LAUNCHES AS PART OF THE INNOVATION150 PILLAR FOR CANADA 150

October
MATTEO MARIANTONI LEADS THE DEVELOPMENT OF THE QUANTUM SOCKET, A NEW 3-D WIRING TECHNIQUE THAT BRINGS SCALABLE QUANTUM COMPUTERS CLOSER TO REALITY

17

January
MICHAL BAJCSY AND TEAM PROPOSES TWO POSSIBLE METHODS FOR BUILDING AN OPTICAL CAVITY INSIDE A HOLLOW-CORE ON-CHIP WAVEGUIDE FOR QUANTUM INFORMATION PROCESSING THROUGH PHOTON-PHOTON INTERACTIONS



March
$10M IN RENEWED FUNDING ANNOUNCED BY THE GOVERNMENT OF CANADA

Quantum *rules*

> “THE BASIC THEORY OF QUANTUM MECHANICS DESCRIBES THE RULES OF HOW OUR WORLD WORKS, BUT WE’RE STILL TRYING TO FULLY UNDERSTAND THE CONSEQUENCES OF THESE RULES.”

There’s an element of predictability when playing chess. Simple rules define how each piece moves in this thoughtful game of strategy. Now imagine playing a game of chess where suddenly the rules have changed. New moves are allowed and the board has dramatically grown in size. This is, in a nutshell, the challenge of studying quantum computing. It’s a very different game than the classical world.

The rules of classical information are based on our everyday human experiences, where objects have definite states that can be completely determined by observing them (at least in principle).

The rules of quantum information, on the other hand, are defined by the principles of quantum mechanics. They explain the behaviour of small particles like atoms, electrons and photons. Objects can exist in a superposition of several states and sequences of moves can interfere with each other. As a result, the outcomes of processes are often counter-intuitive from a classical perspective.

“This is a strange game that nature plays,” said **RICHARD CLEVE**, IQC researcher and IQC Chair in Quantum Computing. “The basic theory of quantum mechanics describes the rules of how our world works, but we’re still trying to fully understand the consequences of these rules.”

Game-changing

Quantum mechanics open up new possibilities for building transformational technologies for computing, healthcare, communications and geological exploration. Cleve’s theoretical research in quantum information theory lays some of the groundwork for programming quantum devices.

“Figuring out what a quantum system is capable of helps guide the exploration of quantum technologies,” said Cleve. “There’s a rich interplay between theory and experiment in the development of architectures for building quantum technologies.”

Cleve has developed some quantum algorithms — sets of instructions that guide quantum mechanical systems — to simulate the evolution of these systems. Designed for quantum computers as small as 50 to 100 qubits, these algorithms move us further along the board towards understanding fundamental quantum behaviour and how we can harness it to build new technologies.

The next move

Cleve joined IQC in 2004. He was an early player to the game when the quantum research community was small. Some even considered quantum information theory to be a risky area of study. But Cleve and his colleagues took the long view and pushed our understanding of quantum and its potential forward. As the field evolves, the fascinating counter-intuitive behaviour of quantum systems keeps Cleve excited as a researcher. He’s ready for the next move.

Qubit by QUBIT

In theory, quantum computing has the potential to exponentially expand the possibilities of information processing. In practice, will it actually outperform a conventional, classical computer?

There's only one way to find out: build a quantum computer and test it.

The task of building a quantum computer combines the exploration of fundamental quantum physics with the challenge of engineering new technologies. It's the perfect scientific mix for IQC researcher **MATTEO MARIANTONI**, also a professor in the Department of Physics and Astronomy.

Inside Mariantoni's Laboratory for Digital Quantum Matter (DQM), superconducting quantum bits (or qubits, the basic unit of quantum information) are carefully studied in an effort to build an extensible quantum processor.

The advantage of superposition

Electronic circuits in classical computers are characterized by two states, 0 and 1. But superconducting qubits can be in a superposition of states, both 0 and 1 at the same time, thanks to quantum mechanics. This ability gives qubits in superposition robust processing power.

Here's the wrinkle: it takes great care to maintain superposition. Quantum mechanical states are very fragile and interact easily with their environment. Interaction with the environment in the circuit eventually causes the qubit to decay and randomly transition from one state to another. As a result, qubits cannot store information for long. "To implement a universal quantum computer, we need to correct and remove those errors caused by interaction and decay," Mariantoni explained.

A logical qubit

In pursuit of quantum-error correction, Mariantoni and his team engineered the quantum socket. It's a three-dimensional wiring technique that connects traditional electronics to quantum circuits using spring-loaded pins for individual qubits. The quantum socket can connect 100 up to 1,000 superconducting qubits in a group called a logical qubit. Grouping the qubits together like this reduces the effects of errors for individual qubits and aligns the error rate more closely to that of a classical computer.

Chip-on-chip bonding

Mariantoni's team also developed a new technology to help qubits maintain a more stable quantum state. Using an etching technique, the team carved a network of tunnels into the surface of a silicon wafer. The tunnels are lined with metal and bonded above the superconducting quantum circuit. The tunnels shield qubits from environmental interferences like electromagnetic fields and increase the length of time data can be stored.

"We believe this approach will significantly improve our ability to control and measure a superconducting qubit," noted Mariantoni. "Combined with the quantum socket, the chip-on-chip bonding technique builds the base of an extensible quantum computing architecture." The DQM lab is paving the way towards the realization of a universal quantum computer, qubit by qubit.

Leading THE NEXT *quantum* REVOLUTION

GRADUATE STUDENTS ARE AN INTEGRAL PART OF OUR SCIENTIFIC COMMUNITY

Message from the Quantum Information Graduate Program Director

Cross-disciplinary research and collaborations among leading computer scientists, engineers, chemists, mathematicians, and physicists create a unique scientific environment at IQC. The Quantum Information Graduate Program, formed in 2010 in partnership with the Faculties of Engineering, Mathematics, and Science, allows students to experience the benefits of this setting and to make fundamentally important contributions to it.

Sixty-seven students have successfully earned PhD degrees and 113 have earned Master's degrees at IQC since its inception. The Quantum Information Graduate Program consistently attracts graduate students of the highest calibre from around the world, and applications have increased by 147 percent over the past seven years.

By engaging in a study of quantum information science through research projects and a wide selection of advanced courses, students in the Quantum Information Graduate Program are trained in a broad range of disciplines and methodologies. Furthermore, graduate students form an integral part of IQC's vibrant research community, often making key contributions and providing insights toward tackling today's research challenges. With the skills and knowledge gained through their studies and research, our students will continue to fuel new discoveries in quantum information research and become tomorrow's scientific leaders.

John Watrous

Quantum Information Graduate Program Director

COURSES

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

Winter 2017

QIC 750
Quantum Information Processing Devices

QIC 823
Quantum Algorithms

QIC 845
Open Quantum Systems

QIC 885
Quantum Electronics and Photonics

QIC 890
Semidefinite Programming in Quantum Information

Spring 2017

QIC 891
Topics in Quantum Safe Cryptography

QIC 890
Introduction to Noise Processes

Fall 2017

QIC 710
Quantum Information Processing

QIC 820
Theory of Quantum Information

QIC 880
Nanoelectronics for Quantum Information Processing

QIC 890
Solid-state Quantum Photonic Devices

QIC 890
Modern Quantum Optics and Nanophotonics

Student *life*

Graduate students play an integral role in IQC's scientific community, extending beyond research contributions. The IQC Graduate Student Association brings students together with social activities and events. Groups such as FemPhys, Let's Talk Science, Waterloo Science Outreach, Engineering Science Quest, Women in Engineering, the Centre for Education in Mathematics and Computing (CEMC) provide opportunities for enriching the academic and community experience.

GRADUATE STUDENTS 2017

Sascha Agne
Arash Ahmadi
Shahab Akmal
Rubayet Al Maruf
Thomas Alexander
Matthew Alexander
Omar Alshehri
Julia Amoros
Matthew Amy
Vadiraj Ananthapadmanabha Rao
Elena Anisimova
Shima Bab Hadiashar
Eduardo Barrera Ramirez
Stefanie Beale
Jérémy Béjanin
Marian Berek
Emma Annelise Bergeron
Kristine Boone
Brendan Bramman
Matthew Brown
Brandon Buonacorsi
Andrew Cameron
Arnaud Carignan-Dugas
Poompong Chaiwongkhot
Christopher Chamberland
Michael Chen
Jiahui Chen
Paulina Corona Ugalde
Yutong Dai
Simon Daley
Patrick Daley
Jose de Ramon Rivera
Tina Dekker
Rahul Deshpande
Olivia Di Matteo
Zhenghao Ding
Ian Dsouza
Carolyn Earnest
Jennifer Fernick
Jeremy Flannery
Nicolas Funai
Kaveh Gharavi
Daniel Grimmer
Lane Gunderman
Aimee Gunther
Holger Haas
Guiyang Han
Laura Henderson
Ian Hincks
Taylor Hornby
Nairong Hou
Anqi Huang
Jaron Huq
Dmitri Iouchtchenko
Tyler Jackson
Samuel Jaques
Andrew Jena
David Jepson
Andrew Jordan
Shitikanth Kashyap
Hemant Katiyar
Maria Kieferova
Feyruz Kitapli
Joel Klassen
Hyeran Kong
Nikhil Kotibhaskar
Meenu Kumari
Dariusz Lasecki
Han Le
Youn Seok Lee
Jason LeGrow
Lin Li
Madelaine Liddy
Piers Lillystone
Jin Gyu Lim
Jun An Lin
Jie Lin
Xudong Liu
Li Liu
Guofei Long
Richard Lopp
David Lou
Benjamin Lovitz
Pei Jiang Low
Jean-Philippe MacLean
Shayan Majidy
Nicolas Manor
Antonio Martinez
Ashutosh Marwah
Christian Mastromattei
Morgan Mastrovich
Somendu Maurya
Michael Mazurek
Thomas McConkey
Emma McKay
Corey Rae McRae
Arthur Mehta
Denis Melanson
Maryam Mirkamali
Abel Molina
Sainath Motlakunta
Mike Nelson
Mohamad Niknam
Joachim Nsofini
Satish Pandey
Maria Papageorgiou
Tarun Patel
Connor Paul-Paddock
Helen Percival
Evan Peters
Clifford Plesha
Mats Powlowski
Jitendra Prakash
Christopher Pugh
Daniel Puzzuoli
Jason Pye
Hammam Qassim
Richard Rademacher
He Ren
John Rinehart
Nayeli Azucena Rodriguez Briones
Theodore Rogozinski
Joshua Ruebeck
Romain Ruhlmann
Vincent Russo
Allison Sachs
Shihan Sajeed
Chung Wai Sandbo Chang
Dusan Sarenac
John Schanck
David Schmid
Ala Shayeghi
Yu Shi
Jiahao Shi
Chung-You Shih
Sumit Sijher
Petar Simidzija
Sebastian Slaman
Nadine Stritzelberger
Nigar Sultana
Huichen Sun
Yongchao Tang
Ramy Tannous
Theerapat Tansuwannont
Burak Tekcan
Archana Tiwari
Sai Sreesh Venuturumilli
Guillaume Verdon-Akzam
Sebastian Verschoor
Cameron Vickers
Dhinakaran Vinayagamurthy
Sean Walker
Zimeng Wang
Chunhao Wang
Christopher Warren
Han Weng
Kyle Willick
Samuel Winnick
Ruoxuan Xu
Yihang Yang
Bowen Yang
Muhammet Yurtalan
Mohd Zeeshan
Shazhou Zhong
Yunda Zhu

POSTDOCTORAL FELLOWS 2017

Razieh Annabestani
Jean-Philippe Bourgoin
Hilary Carteret
Franklin Cho
Patrick Coles
Paulina Corona Ugalde
Matthew Coudron
Javad Doliskani
Ying Dong
Michael Epping
Guanru Feng
Francois Fillion-Gourdeau
Denis Gagnon
Vlad Gheorghiu
Sandra Gibson
Mark Girard
Chris Herdman
Brendon Higgins
Sara Hosseini
Jeongwan Jin
Milad Khoshnegar
Hyun Ho Kim
Sangil Kwon
Jun Li
Ying Liu
Chang Liu
Zhe Liu
Dawei Lu
Zhihuang Luo
Filippo Miatto
George Nichols
Ibrahim Nsanzineza
Geovandro Pereira
Hao Qin
Fereshteh Rajabi
Pooya Ronagh
Mahmood Sabooni
Karthikeyan Sampath Kumar
Francois Sfigakis
Yongchao Tang
Dave Touchette
Peter Tysowski
Joel Wallman
Ben Yager
Taehyun Yoon
Hui Zhang
Pan Zheng

Congratulations

TO OUR RECENT GRADUATES

Razieh Annabestani
PhD Physics
(Quantum Information)

Hillary Dawkins
MSc Physics
(Quantum Information)

John Donohue
PhD Physics
(Quantum Information)

Edward Eaton
MMath Combinatorics and Optimization

Matthew Graydon
PhD Physics
(Quantum Information)

Bappi Golam
MASc Electrical and Computer Engineering
(Quantum Information)

Guiyang Han
MSc Physics
(Quantum Information)

Gregory Holloway
PhD Physics
(Quantum Information)

Sumeet Khatri
MSc Physics
(Quantum Information)

Rui Peng Liu
MMath Combinatorics and Optimization

Xingliang Lou
MMath Combinatorics and Optimization

Xian Ma
MMath Applied Math
(Quantum Information)

Joachim Nsofini
MSc Physics
(Quantum Information)

Alex Parent
MSc Physics
(Quantum Information)

Christopher Pugh
PhD Physics
(Quantum Information)

Vincent Russo
PhD Computer Science

Allison Sachs
MSc Physics
(Quantum Information)

Yongchao Tang
PhD Electrical and Computer Engineering
(Quantum Information)

Guillaume Verdon-Akzam
MMath Applied Mathematics
(Quantum Information)

Zachary Webb
PhD Physics
(Quantum Information)

Yang Yihang
MASc Electrical and Computer Engineering

AWARDS AND RECOGNITION

Faculty Awards and Grants

INCLUDING:

MICHAL BAJCSY
- NSERC Discovery Grant (April 2015)
- Early Researcher Award (April 2017)

JONATHAN BAUGH
- NSERC Discovery Grant (January 2013)
- Gerald Schwartz & Heather Reisman Foundation (March 2015)

KYUNG SOO CHOI
- NSERC Research Tools & Instruments (March 2015)
- Early Researcher Award (April 2015)
- NSERC Discovery Grant (April 2015)

RICHARD CLEVE
- NSERC Operating (April 2013)
- Canadian Institute for Advanced Research (CIFAR) Fellow (July 2013)

DAVID CORY
- Fellowship of the Royal Society of Canada (September 2015)
- Fellow, American Physical Society (October 2015)
- Canada First Excellence Research Fund (September 2016)

THOMAS JENNEWEIN
- Early Researcher Award (May 2011)
- NSERC Discovery Grant (April 2015)
- American Physical Society Outreach Mini-Grant (May 2015)
- Public Works and Government Services Canada/Canadian Space Agency Grant (January 2016)

NA YOUNG KIM
- Early Researcher Award (April 2017)

RAYMOND LAFLAMME
- Quantum Information Science Program, CIFAR (July 2013)
- Waterloo-Technion Cooperation Program (May 2014)
- Canada Research Chair – Tier 1 (February 2016)
- NSERC Discovery Grant (April 2016)
- 2017 CAP-CRM Prize in Theoretical and Mathematical Physics (April 2017)
- 2016 Outstanding Performance Award (May 2017)
- Mike and Ophelia Lazaridis "John von Neumann" Chair in Quantum Information, University of Waterloo (September 2017)
- Order of Canada (December 2017)

DEBBIE LEUNG
- NSERC Discovery Grant (April 2016)

ADRIAN LUPAŞCU
- Waterloo-Technion Cooperation Program (May 2015)

NORBERT LÜTKENHAUS
- NSERC Discovery Grant (April 2012)
- Fellow, American Physical Society (October 2017)

MATTEO MARIANTONI
- NSERC General Research Fund (April 2015)

GUO-XING MIAO
- Early Researcher Award (April 2017)

MICHELE MOSCA
- NSERC Create Grant (March 2012)
- Canadian Foundation for Innovation (CFI) Leading Edge Fund (February 2013)
- Ontario Research Fund (February 2013)
- NSERC Discovery Grant (March 2014)
- Quantum Information, CIFAR (June 2014)
- Fr. Norm Choate C.R., Lifetime Achievement Award (May 2017)

ASHWIN NAYAK
- NSERC Discovery Grant (April 2014)
- Canadian Queen Elizabeth II Diamond Jubilee Scholarship (January 2015)

VERN PAULSEN
- NSERC Discovery Grant (April 2016)

MICHAEL REIMER
- NSERC Discovery Grant (April 2016)
- Early Researcher Award (April 2017)

KEVIN RESCH
- FQXi Physics of What Happens (September 2015)
- NSERC Research Tools & Instruments (March 2016)
- NSERC Discovery Grant (April 2017)

JOHN WATROUS
- NSERC Research Grant (January 2007, April 2014)
- 2014 Outstanding Performance Award (June 2015)

CHRISTOPHER WILSON
- Ontario Centres of Excellence Award (November 2015)
- 2016 Marsland Family Award (March 2017)

Student Awards

Earned by IQC Master's and PhD students in 2016-2017 including:

David R. Cheriton Graduate Scholarship
TAYLOR HORNBY
LI LIU
ABEL MOLINA
DHINAKARAN VINAYAGAMURTHY

IQC Achievement Award
KENT FISHER
MEENU KUMARI
MICHAEL MAZUREK
CHRISTOPHER PUGH
SHIHAN SAJEED
DUSAN SARENAC

IQC David Johnston Award for Scientific Outreach
SIMON DALEY
DARRYL HOVING
JEAN-PHILLIPE MACLEAN

IQC Entrance Award
ANDREW CAMERON
SIMON DALEY
NICHOLAS MANOR
CLIFFORD PLESHA
NAYELI AZUCENA RODRIGUEZ BRIONES
PETAR SIMIDZJIA
GUILLAUME VERDON-AKZAM

Recognizing SCIENTIFIC OUTREACH AND COMMUNITY ENGAGEMENT

Congratulations to JEAN-PHILIPPE MacLEAN and DARRYL HOVING, recipients of the 2016 IQC David Johnston Award for Scientific Outreach. This award, created in honour of His Excellency DAVID JOHNSTON, Canada's Governor General from 2010-2017, recognizes students who have shown an outstanding commitment to scientific outreach and community engagement.

MacLean played a role in the development of *LIGHT Illuminated* in celebration of the UN's International Year of Light and is an active leader at IQC's Undergraduate School for Experimental Quantum Information Processing (USEQIP). Hoving was recognized for his leadership introducing high school students to the ideas of modern physics, including quantum information science.

Mike and Ophelia Lazaridis Fellowship — Master's
EMMA BERGERON
YOUN SEOK LEE
LIN LI
MORGAN MASTROVICH

Mike and Ophelia Lazaridis Fellowship — PhD
NICHOLAS FUNAI
SARAH KAISER
MARIA KIEFEROVA
MEENU KUMARI
LI LIU
ABEL MOLINA
HAMMAM QASSIM
NAYELI AZUCENA RODRIGUEZ BRIONES
DAVID SCHMID
SUMIT SIJHER
YONGCHAO TANG

NSERC Alexander Graham Bell Canada Graduate Scholarship — Doctoral
MATTHEW AMY
OLIVIA DI MATTEO
JOHN DONOHUE
LAURA HENDERSON
JASON LEGROW
MICHAEL MAZUREK
CHRISTOPHER PUGH
JASON PYE
JEFFREY SALVAIL
SEAN WALKER
CHUNHAO WANG
KYLE WILLICK

NSERC Alexander Graham Bell Canada Graduate Scholarship — Master's
STEFANIE BEALE
KRISTINE BOONE
ANDREW CAMERON
PATRICK DALEY
HONGHAO FU
SAMUEL JAQUES
JASON LEGROW
JUNAN LIN
JASON PYE
PETAR SIMIDZIJA
RAMY TANNOUS

NSERC Postgraduate Scholarship — Doctoral
ARNAUD CARIGNAN-DUGAS
CHRISTOPHER CHAMBERLAND
AIMEE GUNTHER
GREG HOLLOWAY
GUILLAUME VERDON-AKZAM

NSERC Vanier Canada Graduate Scholarship
DANIEL GRIMMER
TOMAS JOCHYM-O'CONNOR
JEAN PHILIPPE MACLEAN

Ontario Graduate Scholarship
SHIMA BAB HADIASHAR
EDUARDO BARRERA RAMIREZ
STEFANIE BEALE
KRISTINE BOONE
HILLARY DAWKINS
KENT FISHER
JEREMY FLANNERY
TAYLOR HORNBY
DMITRI IOUCHTCHENKO
SUMEET KHATRI
DAVID LAYDEN
CHRISTIAN MASTROMATTEI
CHRISTOPHER PUGH
DANIEL PUZZUOLI
JOSHUA YOUNG

President's Graduate Scholarship
MATTHEW ALEXANDER
MATTHEW AMY
SHIMA BAB HADIASHAR
EDUARDO BARRERA RAMIREZ
STEFANIE BEALE
KRISTINE BOONE
ANDREW CAMERON
ARNAUD CARIGNAN-DUGAS
CHRISTOPHER CHAMBERLAND
PATRICK DALEY
HILLARY DAWKINS
OLIVIA DI MATTEO
JOHN DONOHUE
KENT FISHER
JEREMY FLANNERY
HONGHAO FU
DANIEL GRIMMER
AIMEE GUNTHER
LAURA HENDERSON
GREG HOLLOWAY
TAYLOR HORNBY
DMITRI IOUCHTCHENKO
SAMUEL JAQUES
SUMEET KHATRI
DAVID LAYDEN
JASON LEGROW
JUNAN LIN
CHRISTIAN MASTROMATTEI
MICHAEL MAZUREK
CHRISTOPHER PUGH
DANIEL PUZZUOLI
JASON PYE
JEFFREY SALVAIL
PETAR SIMIDZIJA
ALA SHAYEGHI
RAMY TANNOUS
GUILLAUME VERDON-AKZAM
SEAN WALKER
CHUNHAO WANG
KYLE WILLICK
JOSHUA YOUNG

Provost Doctoral Entrance Award for Women
JENNIFER KATHERINE FERNICK
NAYELI AZUCENA RODRIGUEZ BRIONES
ALLISON SACHS
NADINE STRITZELBERGER

Queen Elizabeth II Graduate Scholarship in Science and Technology
MATTHEW ALEXANDER
KRISTINE BOONE
MATTHEW BROWN
CHRISTOPHER CHAMBERLAND
DANIEL PUZZUOLI
ALA SHAYEGHI

Public Outreach and Informing the Public Grants
AIMEE GUNTHER

Outstanding Achievement in Graduate Studies
NAYELI AZUCENA RODRIGUEZ BRIONES

Dean of Science Award
NAYELI AZUCENA RODRIGUEZ BRIONES

CAP-OSAF Boris P. Stoicheff Memorial Scholarship
CHRISTOPHER PUGH

Ontario Trillium Scholarship
NADINE STRITZELBERGER

“TO SEE SOMETHING FINALLY COME TOGETHER AFTER WORKING TOWARDS IT FOR SO LONG FEELS VERY REWARDING.”

A *skillful* APPROACH

CHRISTOPHER PUGH, PHD STUDENT

Manitoba native CHRISTOPHER PUGH wanted a graduate program that would provide relevant, real-world training and the opportunity to gain transferable skills for both academic and industrial career paths. He found the right fit at the University of Waterloo in the Department of Physics and Astronomy, studying Physics (Quantum Information) as a member of IQC.

Pugh researches free space propagation of quantum information signals over long distances for the purpose of secure quantum communication, specifically quantum key distribution (QKD). QKD uses the laws of quantum mechanics to establish a shared key that is secure and independent of any other data, provided the two parties also share a classical authenticated channel. The potential to share quantum keys globally opens up with a satellite network where quantum keys can be distributed from ground stations located around the world to satellite stations and back.

The Quantum Encryption and Science Satellite (QEYSSat) mission aims to generate encryption keys through the creation of quantum links between ground and space. Pugh’s involvement with the QEYSSat mission began six years ago when starting his Master’s degree under the supervision of IQC researcher and QEYSSat Principal Investigator **THOMAS JENNEWEIN**.

Pugh played a major role in achieving a successful QEYSSat milestone as the technical lead on the development of the Quantum Key Distribution Receiver Acquisition, Pointing and Tracking (QKDR APT) system in collaboration with industry partners, including the Canadian Space Agency (CSA). “We performed successful QKD over a longer distance than we previously demonstrated with the fine pointing unit,” said Pugh. “It was a crucial step to bringing the QEYSSat project closer to a future quantum space mission.”

Pugh’s research goes up from there — literally. Recently, he was part of the first successful transmission of a secure quantum key from a source on the ground to a quantum satellite receiver prototype on board a National Research Council of Canada (NRC) aircraft. After a week of meticulous testing to certify that all equipment was airworthy, Pugh took to the sky in the NRC aircraft where he used the fine pointing unit and other custom systems to receive photons and extract a quantum key sent from a photon source on the ground. “Receiving the photons in the air was definitely a highlight,” recalled Pugh. “This was a real team effort. To see something finally come together after working towards it for so long feels very rewarding.”

The rewards extend beyond research for Pugh. Recognized with the IQC David Johnston Award for Scientific Outreach in 2013, he is actively involved in outreach activities. He’s even co-hosted the Q-Kids science show with Scientific Outreach Officer **ELECTRA ELEFTHERIADOU**. “I’ve really enjoyed the opportunities to participate in outreach at IQC,” said Pugh. “It’s given me a chance to develop new skills, give back to the community and to share my passion for science with others.”

Quantum science heading to space

IQC is pioneering new applications for quantum technologies, in particular quantum communications networks via satellite. Collaborating with other IQC researchers, Principal Investigator **THOMAS JENNEWEIN** leads the QEYSSat team in pursuit of the implementation of global scale quantum key distribution and perform tests of quantum science over large distances.

QEYSSAT PROJECT MILESTONES

2010 — Preliminary technology feasibility studied with Defense Research and Development Canada (DRDC).

2011 — Feasibility study with the Canadian Space Agency (CSA).

2012 — Development of technological payload concepts in the IQC laboratory.

2013 — Hardware prototyping and market study with funding from FedDev Ontario.

2014 — Completion of CSA-funded payload prototype development.

2015 — Technology development for tracking sub-system and detector assembly.

Exchange of secure key in demonstration of QKD from a stationary source to a moving receiver.

Successful laboratory demonstration of a form, fit and function prototype of QKDR.

2016 — Successful transmission of a quantum key securely from a source on the ground to a receiver on an aircraft.

Completion of a realistic satellite concept of a micro-satellite bus housing the quantum receiver payload.

2017 — Successful tests of the detector prototype under environmental conditions.

IQC ALUM

THE NEXT GENERATION OF SCIENTIFIC LEADERS LEAVE IQC WITH THE RESEARCH SKILLS AND INTERDISCIPLINARY INSIGHT NEEDED TO NAVIGATE THE EVER-CHANGING LANDSCAPE OF DISCOVERY IN AREAS OF ACADEMIA, INDUSTRY AND GOVERNMENT.

Sarah Sheldon,

POSTDOCTORAL FELLOW 2013

During her most recent return to IQC, former postdoctoral fellow **SARAH SHELDON** instructed a session on IBM's Quantum Experience, a cloud-enabled quantum processor, with a room of Undergraduate School on Experimental Quantum Information Processing (USEQIP) participants. Sheldon is part of the experimental quantum computing team at IBM Research that is currently pursuing a quantum computing architecture based on superconducting qubits and error corrections through surface code. She is developing new calibration and characterization techniques to better understand the errors present in the quantum system.

"The research I did while at IQC was very relevant for my current position with IBM," said Sheldon. She earned her PhD at the Massachusetts Institute of Technology (MIT) in Nuclear Science and Engineering with advisor **DAVID CORY**. Sheldon studied nuclear magnetic resonance (NMR) and electron spin resonance (ESR), focusing mostly on dynamic nuclear polarization (DNP) and quantum control. As a postdoctoral fellow at IQC, Sheldon was exposed to different approaches to quantum computing research that motivated her to select a research group that incorporated both theory and experiment, engineering as well as basic science. "Quantum computing is such an interdisciplinary field. I think it's beneficial to be in a research community like IQC or IBM where there are many people with wide-ranging interests and backgrounds within the broader field."

Agnes Ferenczi,

PhD 2013

When faced with a challenge, **AGNES FERENCZI** sees an opportunity for discovery. Ferenczi currently investigates a variety of areas including machine learning, software development, user experience and search algorithm implementations at Cliqz, a search engine and browser company focused on privacy. Here, she uses the research tools and skills she developed during her PhD research on quantum cryptography with IQC researcher **NORBERT LÜTKENHAUS**.

With an emphasis on security proofs for quantum cryptography systems, Ferenczi adapted quantum theories to match current experimental capabilities, bridging the gap between theory and experimental reality. Her PhD research included a revision to the phase encoded BB84 protocol where quantum information is transmitted using photon polarization. In this scenario, one party sends out two laser pulses. One laser pulse stays the same and the other weakens, a result that was not initially accounted for in the theoretical proof. "We adapt the proof to allow for imperfections in the experimental environment," said Ferenczi. Simplifying the proof for experimental implementation often improves accessibility for experimentalists.

Donny Cheung,

MASTER'S 2002, PhD 2007

DONNY CHEUNG was one of the very first graduate students at IQC. "It's been amazing to watch IQC grow," recalled Cheung. He remembers the excitement surrounding the official launch of IQC in 2002 and moving into the first IQC graduate student office space in the Math and Computer building at the University of Waterloo.

Under the supervision of researcher **MICHELE MOSCA**, Cheung's research focused on approximate phase estimation algorithms, the quantum separability problem and quantum cellular automata. Cheung found the free and open flow of discussion on challenging problems and interesting ideas among researchers rewarding. The interdisciplinary research environment at IQC encouraged him to think broadly while considering connections between different scientific fields at the smallest scale. Cheung takes a similar research-based approach to challenges in his current role as a software engineer at Google where he is working on the Google Cloud Platform.

IQC TO THE WORLD

GREAT RESEARCH MUST BE SHARED WITH THE PEOPLE WHO SUPPORT IT, WHO ARE FASCINATED BY IT, AND WHO ULTIMATELY WILL BENEFIT FROM IT

Scientific OUTREACH

IMPACTFUL OUTREACH FUELS THE NEXT GENERATION OF SCIENTIFIC LEADERS AND ENCOURAGES INNOVATIVE EXPLORATION AND DISCOVERY. IQC BRINGS THE WORLD OF QUANTUM INFORMATION SCIENCE AND TECHNOLOGY TO THE CURIOUS-MINDED THROUGH UNIQUE OPPORTUNITIES DESIGNED TO SHARE THE FASCINATING RESEARCH THAT IS CHANGING THE WAY WE LIVE, WORK AND PLAY.

IN 2017 IQC HOSTED:

4 **conferences, including:**

- Women in Physics Canada, *July 26-28*
- Quantum Key Distribution Summer School, *August 21-25*

4 **workshops, including:**

- Quantum Innovators in Computer Science and Mathematics, *September 18-22*
- Quantum Innovators in Science and Engineering, *October 2-5*

42 **seminars**

24 **colloquia**

AND SPONSORED

15
workshops and conferences around the world.

Face-to-face with future researchers

4,826
participated in

91
outreach programs, lectures and workshops promoting quantum science and technology, including:

2,585
high school students

98
elementary students

239
educators

Talking quantum

Public lecture
Quantum Applications: What will a quantum device do?

1,551
online views

Lecture Series:
Women in Physics Canada
Sharing research by and insight for early career women in science

8
lectures

4,232
online views

Digital quantum learning

36,561
online visitors to Quantum Computing 101

1,301,458
minutes of quantum talks watched in 200 countries

TEACHING TEACHERS QUANTUM

Through lectures and hands-on activities, 36 science educators took their turn as students at Schrödinger's Class. They learned about integrating quantum technology into the current teaching curriculum and gained the tools to share quantum with their classes.

Schrödinger's Class

QCSYS

Quantum Cryptography School for Young Students

The QCSYS program engages high school students with one of the most exciting topics in contemporary science — quantum cryptography. Led by Senior Manager, Scientific Outreach MARTIN LAFOREST, students explore the physics and mathematics of quantum mechanics and cryptography through lectures and hands-on lab demonstrations.

Dinah Shi, QCSYS 2012

Cryptography, quantum theory and their intersection were among the new topics introduced to **DINAH SHI** at QCSYS. She was fascinated by the real implications of quantum cryptography on everyday life: "A quantum algorithm could render cryptography based on factoring large composite integers insecure, and that's dangerous." The lecturers, faculty members and graduate students also inspired Shi. "They were clearly passionate about this highly advanced, niche subject. It made me want to discover a technical topic that I could get excited about and become a master at my craft."

Now a fourth year undergraduate student studying software engineering at the University of Waterloo, Shi is well on her way to mastering her craft. She plans to someday use her skills as a programmer in industry, investigating how technology affects end-consumers and businesses. Currently, Shi leads the Waterloo chapter of Women Who Code, a program that inspires women to excel in careers in technology by organizing tech talks, panels and networking events. Her advice for future QCSYS students: "Come ready to learn!"

Since 2008, there are

361 QCSYS alumni from **29** countries across the globe

Turner Silverthorne, QCSYS 2015

"QCSYS presented physics in a very organic way," remembered QCSYS alumnus **TURNER SILVERTHORNE**. He felt an immediate sense of belonging and connection through his shared passion for physics and discovery with fellow QCSYS students. Exploring math and physics at QCSYS was a unique experience, similar to an improvised guitar performance. A talented musician, Silverthorne often uses music as an analogy when talking about physics. "Physics is like playing the guitar — anyone can learn it, you just need to practice."

He is gaining plenty of physics practice studying mathematical physics as an undergraduate student at the University of Waterloo. Silverthorne's most recent co-op term brought him back to IQC as an Undergraduate Research Assistant (URA) with faculty member **MICHAL BAJCSY** to investigate novel applications of light-matter interaction. He is working on finalizing the design of a miniaturized ion trap with a built-in optical cavity. By balancing photon confinement with ion trap stability, his research aims to find the optimal platform for light-matter interaction within an ion trap.

43
QCSYS participants this year from 10 countries explored the physics and mathematics of quantum mechanics and cryptography

96%
increase in QCSYS applications since 2012

USEQIP

Undergraduate School on Experimental Quantum Information Processing

The two-week program, USEQIP, combines both a theoretical and experimental approach to studying quantum information for international senior post-secondary students. Lectures by IQC faculty members followed by hands-on exploration in experimental facilities provide a well-rounded introduction to quantum information science and technology. USEQIP alumni leave the program equipped with the tools to begin investigating the quantum information field.

USEQIP participants are encouraged to apply to the Undergraduate Research Award (URA) program, a fully-funded research experience at IQC offered to as many as 30 students annually. Students spend the summer term working with a faculty member, exposing them to real quantum information research and what life as a graduate student at IQC is like. "Showing young students the beauty and importance of quantum information science and technology may attract new researchers to the field," said MARTIN LAFOREST, IQC's Senior Manager, Scientific Outreach. "These students will be the ones making groundbreaking discoveries in the future, finding new applications for quantum devices and proposing fresh ideas."

Thomas Alexander, USEQIP 2013

Growing up on Canada's east coast, **THOMAS ALEXANDER** was always interested in science. It wasn't until his undergraduate years at Mount Allison University where he studied physics and minored in both computer science and mathematics that he was first introduced to the field of quantum information. "I was intrigued with quantum computing because it combined my love of physics and computer science," said Alexander. "I took an online course in quantum information theory to learn more."

Alexander applied to USEQIP after one of his professors suggested it would be right up his alley. His professor was right — Alexander felt USEQIP was the perfect fit. He enjoyed the engaging lectures, but his favourite part was getting hands-on with experiments in the lab. The USEQIP experience prepared him for the time he spent afterwards as an Undergraduate Research Assistant (URA) with IQC faculty member **DAVID CORY** and former PhD student **CHRISTOPHER GRANADE**. Alexander contributed to the hardware and software aspects of an experimental system at IQC connected to neutron interferometers located at the National Institute of Standards and Technology (NIST) in Maryland, USA. He wrote his honours undergraduate thesis on the work.

Now, he's returned to IQC as a Master's student studying physics and quantum information with Cory, his former URA supervisor. He even volunteers as a USEQIP leader for the nuclear magnetic resonance (NMR) lab at USEQIP. "My experience at USEQIP led me on a career trajectory that I didn't think was achievable at the time," attested Alexander. He is currently studying silicon phosphorous with NMR, an interesting system that could be useful for quantum computing and quantum sensing. "There are very few places in the world that have the critical mass of expertise in quantum information science that IQC does. This is the best place to study experimental quantum computing in Canada."

Morgan Mastrovich, USEQIP 2015

From the top of a tower, the view is vast and wide; at a high-level, the details may be blurry but there is a holistic picture of the landscape below. USEQIP was **MORGAN MASTROVICH**'s quantum tower — the experience gave her a broad overview of the quantum information science research field. "USEQIP provided a great first exposure to the wider landscape of the quantum world," recalled Mastrovich. "It was an excellent opportunity to grasp an understanding of the research field as a whole."

Mastrovich now explores the quantum landscape in greater detail. Following USEQIP, she spent the summer as an Undergraduate Research Assistant (URA) researching quantum optics with IQC faculty member and Canada Research Chair in Optical Quantum Technologies **KEVIN RESCH**. The interdisciplinary nature of the institute appealed to Mastrovich, and she returned last fall to the University of Waterloo as a Master's student to study physics and quantum information.

In collaboration with IQC faculty member **MICHAEL REIMER**'s lab, Mastrovich is working towards producing polarization entangled states by interfering single photons emitted by a quantum dot encased in a nanowire waveguide. The experiment is intended to demonstrate an interesting application of quantum dots as an effective single photon source. "The advantage of using the quantum dot as a single photon source is that it's brighter than other traditional sources and is much less likely to produce pairs," explained Mastrovich. She admitted it can be easy to get tunnel vision when working on the details of a project, but appreciates how it's just as easy to access experts in all areas of quantum research at IQC when in need of a fresh perspective.

24
outstanding participants learned the theoretical and experimental foundations of quantum information processing

17
USEQIP participants stayed for an Undergraduate Research Award (URA)

69%
increase in USEQIP a pplications since 2012

Celebrating Canada150 WITH INNOVATION150

Minister of Canadian Heritage, the Honourable MÉLANIE JOLY unveiled Innovation150 and almost $6 million in funding from the Government of Canada at the Discovery Centre in Halifax, Nova Scotia in March 2016. Canadian astrophysicist and winner of the 2015 Nobel Prize in Physics, ARTHUR McDONALD, the official ambassador for Innovation150, was also on hand to welcome the project partners: IQC, Perimeter Institute for Theoretical Physics, Actua, the Canada Science & Technology Museums Corporation and the Canadian Association of Science Centres. An interactive, year-long celebration of Canadian ideas, ingenuity and innovation, the Innovation150 project brings experiences in science and technology to communities across the country for Canada's 150th anniversary.

IQC SHARES QUANTUM INFORMATION SCIENCE AND TECHNOLOGY FROM COAST TO COAST TO COAST

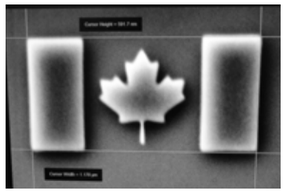
"Canada's 150th anniversary is an ideal time to celebrate great Canadian science and bring quantum science to Canadians across the country," said **TOBI DAY-HAMILTON**, IQC's Director, Communications and Strategic Initiatives. "The research that is happening at IQC and at other institutes across the country is too important to stay in the labs. A lot of amazing quantum research takes place right in our own backyard and we want to share this great work with our fellow Canadians."

How do you take a complex topic like quantum mechanics, a concept that redefines our understanding of nature, and make it accessible to everyone? The answer: you build an interactive science exhibition about it. *QUANTUM: The Exhibition* premiered downtown Kitchener at THEMUSEUM on October 13, 2016. Special guests not only had the opportunity to see the exhibition before anyone else, but they also saw a surprise video message from world-renowned theoretical physicist **STEPHEN HAWKING** for his former student, **RAYMOND LAFLAMME**, congratulating him on his advocacy to share quantum science with the world.

"In many ways, Canadian researchers are leading the development of new quantum technologies that will transform our lives," explained Laflamme. "This exhibition explores these technologies and how they will inevitably change the world." The exhibition travelled across Canada in 2017 including stops in Vancouver, Calgary, Saskatoon, Halifax and Ottawa.

"We often hear from people that quantum science is intimidating," said Day-Hamilton. "From the beginning, our goal in developing *QUANTUM* was to engage people of all ages in a fun and unique way. We want everyone to have an understanding of how quantum technologies will change their lives."

Special guests gathered at the October 13 launch of *QUANTUM: The Exhibition*. Pictured left to right is University of Waterloo President and Vice-Chancellor **FERIDUN HAMDULLAHPUR**, the Honourable **BARDISH CHAGGER**, IQC Senior Manager, Scientific Outreach **MARTIN LAFOREST**, IQC Executive Director **RAYMOND LAFLAMME**, Mayor of Waterloo **DAVE JAWORSKY**, the Honourable **KIRSTY DUNCAN**, MP **RAJ SAINI**, MPP **DAIENE VERNILE**, Councillors **ANGELA VIETH** and **JEFF HENRY**, IQC Director, Communications and Strategic Initiatives **TOBI DAY-HAMILTON** and MP **HAROLD ALBRECHT**.



The Smallest National Flag travelled across Canada with *QUANTUM: The Exhibition*. IQC's GUINNESS WORLD RECORDS™ record title for Smallest National Flag measures 1.178 micrometres in length and is invisible without the aid of an electron microscope.

> "*QUANTUM: THE EXHIBITION* IS A CELEBRATION OF OUR RESEARCHERS, AND WHAT WE HAVE ACCOMPLISHED SO FAR...YOU'LL EXPLORE WHAT QUANTUM MECHANICS MEANS FOR THE FUTURE OF TECHNOLOGY. YOU'LL SEE THAT THE POSSIBILITIES ARE ENDLESS, AND THAT QUANTUM COMPUTING TRULY HAS THE POTENTIAL TO TRANSFORM OUR WORLD."
>
> **Justin Trudeau,**
> *Prime Minister of Canada*

24 researchers and
1 prime minister contributing

Travelling 12,732 km across
Canada in 1 year

The year IN REVIEW: Looking *back*, looking *forward*

BACKSTAGE IS BUSTLING WITH ACTIVITY. A PEEK BEHIND THE SCENES OF ANY SUCCESSFUL THEATRICAL PRODUCTION REVEALS THE INVOLVEMENT OF AN ENTIRE CREW, EACH MEMBER CONTRIBUTING TO SOME ASPECT OF THE SHOW — FROM SET DESIGN, TO WARDROBE, TO LIGHTING OR SOUND — WITHOUT EVEN SETTING FOOT ON STAGE. "THE ADMINISTRATION TEAM IS LIKE THE BACKSTAGE CREW," COMPARED **LORNA KROPF**, ASSISTANT DIRECTOR, ADMINISTRATION. "WE WORK BEHIND THE SCENES TO SUPPORT IQC FACULTY MEMBERS AND THEIR RESEARCH."

Behind the scenes

LORNA KROPF,
ASSISTANT DIRECTOR, ADMINISTRATION

Kropf has led IQC's administration team for nine years. "I was very excited for the opportunity to join a young institute and to be part of its growth," recalled Kropf. She has guided the administration team through many changes, such as onboarding 17 new faculty members and coordinating two building moves.

Without taking center stage, Kropf takes pride in the tasks that are fundamental to the operational success of the institute. Her team offers support, including account management and grant proposal preparation, for each faculty member. "Our team aims to provide exceptional service for our researchers so that they can focus on their research and teaching," said Kropf.

The administration team also supports several committees, plays a lead role in shaping the visitor experience, administers the quantum information graduate program and manages the frontline interactions with all who visit the institute on a daily basis. "We are representing IQC and building a culture of excellence here."

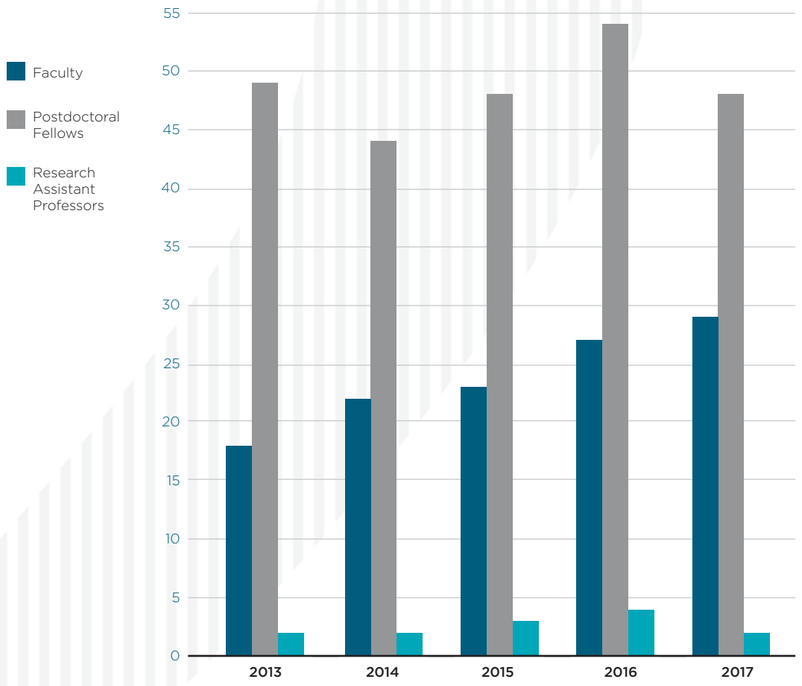
Looking ahead, Kropf stated that a proactive approach to improving processes and developing tools to streamline administrative tasks will allow the team to continue providing exceptional service. According to Kropf, "The administration team needs to be adaptable to the changing needs of our researchers and the institute as it continues to grow."

Kropf knows how to navigate change at IQC. "I remember the Lazaridis Centre as a cardboard model, and now this building has come to life," she said. "This is an exciting place to be. We are supporting world-changing research." The administration team is ready, backstage, to support the institute moving forward.

IQC BY THE *numbers* 2017

IQC IS HOME TO: 29 FACULTY MEMBERS, **48** POSTDOCTORAL FELLOWS, **171** GRADUATE STUDENTS, **42** LONG-TERM VISITORS AND **7** TECHNICAL SPECIALISTS.

Faculty & Postdoctoral Fellows



Publications

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

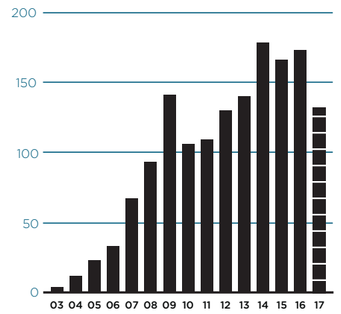
IQC RESEARCH PUBLISHED IN PROMINENT JOURNALS SINCE 2013

PUBLICATION	2013	2014	2015	2016	2017
Nature		2	1		1
Science	1	1			
Nature Photonics	3	2		3	
Nature Physics	3		2		2
Nature Communications	1	7	2	5	3
Physical Review Letters	15	20	23	11	6
Journal of Mathematical Physics	4	5	4	5	5
FOCS		2	2	1	
STOC		1		1	
TOTAL	27	40	34	26	17

Publications by IQC Researchers

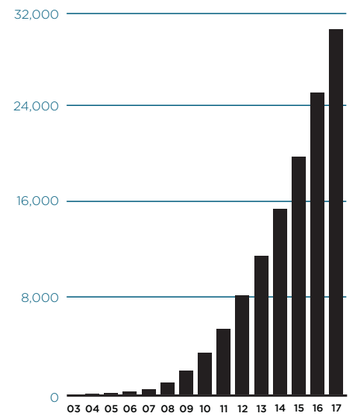
132 publications by IQC researchers in 2017

1,507 publications by IQC researchers since 2002



Cumulative Citations of IQC Publications

30,435 cumulative citations for all IQC publications since 2002



Note: Source for publications (2017 partial year) and citations: Thomson Reuters' Web of Science on December 18, 2017. Data compiled using an address search for Institute for Quantum Computing (inst quantum comp*). Citations are cumulative for all IQC publications for all years.*

IQC GOVERNANCE 2017

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Laboratory Support

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Executive Assistant to the Director

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Receptionist, Lazaridis Centre

Maren Butcher
Receptionist, Lazaridis Centre

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Administrative Coordinator/Financial Assistant

Monica Dey
CREATE and Graduate Program Coordinator

Christine Dietrich
Receptionist, RAC 1

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Research Support Assistant

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Harmeny Storer
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Scientific Outreach Officer

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Siobhan Stables
Senior Manager, Research Insights

Jodi Szimanski
Senior Manager, Communications

GLOBAL LEADERSHIP IN THE REVOLUTIONARY FIELD OF QUANTUM RESEARCH

Message from the President of the University of Waterloo

IQC was built on new ideas — harnessing quantum mechanics and breakthrough technologies to solve tomorrow's problems *today*.

In 2002, a new kind of institute was born at the heart of an innovation ecosystem in Waterloo — the Institute for Quantum Computing. This globally-recognized institute epitomizes, as Stephen Hawking so aptly notes of us, taking ideas "from theory to experiment and beyond."

Going beyond is what we do at the University of Waterloo, which makes IQC a perfect fit. Waterloo itself was founded on new ideas — commitment to co-operative education, world-class scholarship, and deep connection to industry that results in research and teaching that helps solve some of the most complicated global problems.

Waterloo recognizes that solutions to the greatest challenges of tomorrow rely on reaching across disciplines, institutions, industries and nations. They rely on world-class research, and on training a new generation of scientists.

Since its inception, IQC has embodied these goals and more. The Institute represents a unique collaborative effort among three Faculties at Waterloo — Engineering, Math and Science. The Institute is a magnet for many of the world's best minds in quantum information science.

And among the best of the best is Raymond Laflamme. I would like to take this opportunity to commend and thank Raymond for his visionary leadership of the Institute as Founding Director and for his many contributions. From the beginning, he has played a vital role in making the Institute's vision a reality.

The University of Waterloo and IQC are putting Canada on the map as we provide global leadership in the revolutionary field of quantum research and technology. The Institute is steadily increasing its complement of faculty, postdoctoral fellows, and students. And we are leading the way in the next great technological revolution — the quantum revolution.

As the pace of change is accelerating with every new discovery in quantum technologies, Waterloo has a front row seat for the high-speed journey ahead.

Feridun Hamdullahpur
PRESIDENT AND VICE-CHANCELLOR

University of Waterloo

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing