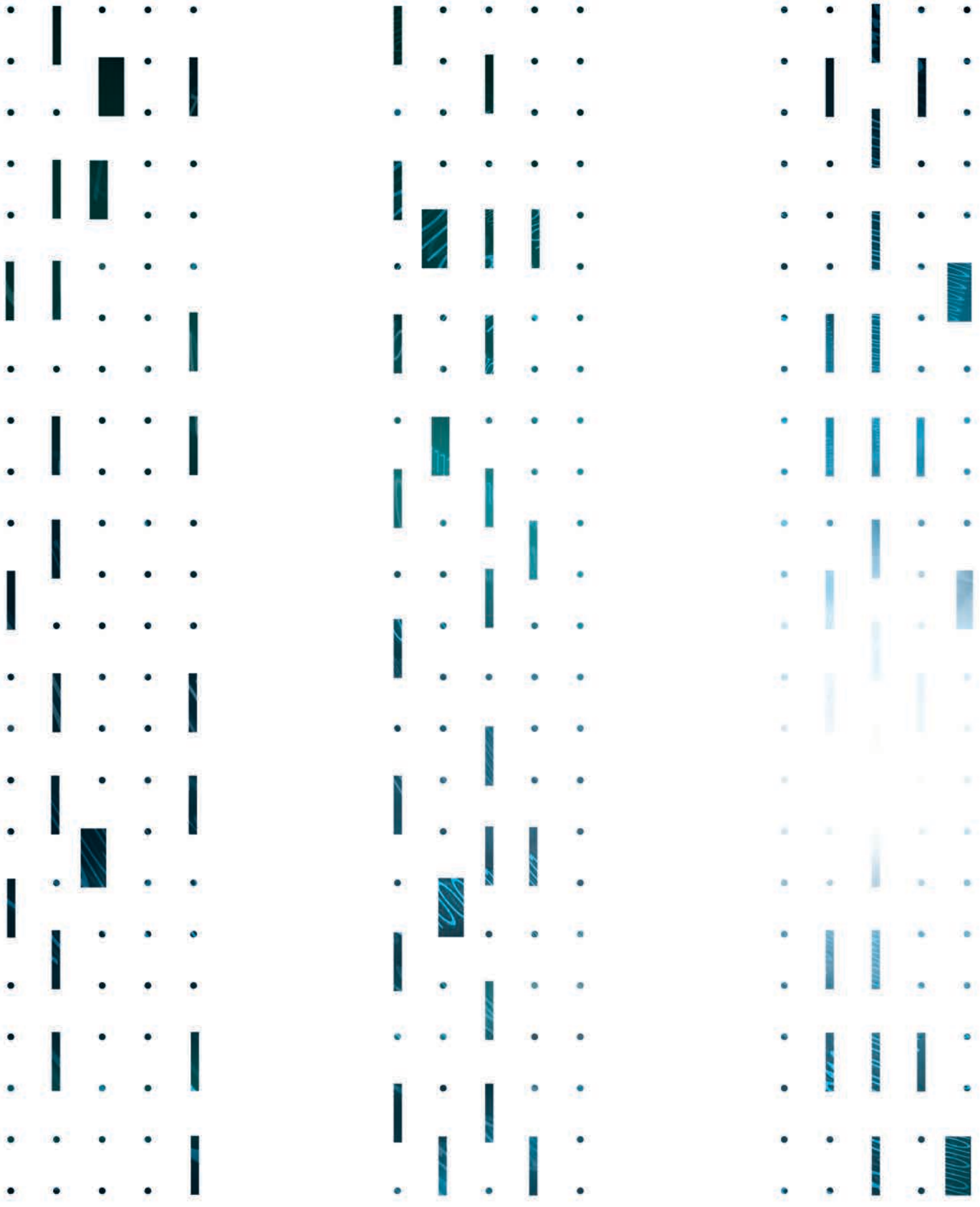

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

BUILDING THE QUANTUM VALLEY

ANNUAL REPORT 2016

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

"IQC AND THE UNIVERSITY OF WATERLOO ARE POSITIONING CANADA TO LEAD THE WORLD IN QUANTUM RESEARCH AND IN DEVELOPING THE NEW COMPANIES THAT WILL BUILD THE QUANTUM INFORMATION SCIENCE INDUSTRY."

FERIDUN HAMDULLAHPUR,
PRESIDENT AND VICE-CHANCELLOR,
UNIVERSITY OF WATERLOO

PUBLISHED BY IQC COMMUNICATIONS AND STRATEGIC INITIATIVES

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Kathryn Fedy
Alex Rollinson
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EMAIL: IQC@UWATERLOO.CA

BUILDING THE QUANTUM VALLEY

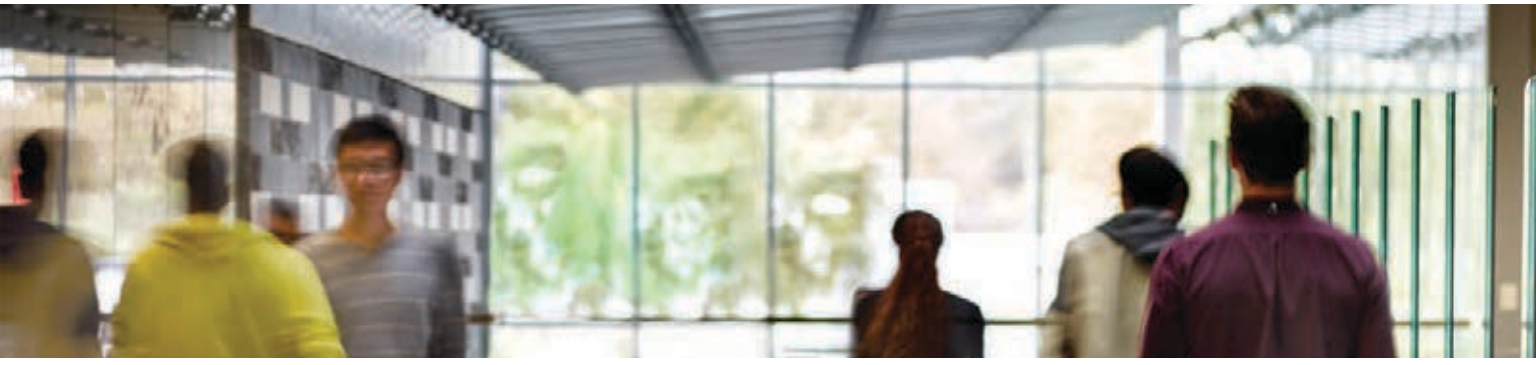
ANNUAL REPORT 2016

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

THE DRIVE FOR EXCELLENCE AND INNOVATION AT THE INSTITUTE FOR QUANTUM COMPUTING

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.

STRATEGIC OBJECTIVES

1. TO ESTABLISH WATERLOO AS A WORLD-CLASS CENTRE FOR RESEARCH IN QUANTUM TECHNOLOGIES AND THEIR APPLICATIONS.
2. BECOME A MAGNET FOR HIGHLY QUALIFIED PERSONNEL IN THE FIELD OF QUANTUM INFORMATION.
3. TO BE A PRIME SOURCE OF INSIGHT, ANALYSIS AND COMMENTARY ON QUANTUM INFORMATION.

CORE RESEARCH AREAS

QUANTUM COMPUTING

Exploring quantum information, using atoms, molecules and particles of light to create new bits of information – qubits – instead of electrical circuit elements to create 0s and 1s 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.

GROWING A QUANTUM INDUSTRY

MESSAGE FROM THE EXECUTIVE DIRECTOR

FOURTEEN YEARS AGO A SEED WAS PLANTED AT THE UNIVERSITY OF WATERLOO. WHAT STARTED AS A VISION TO TRANSFORM FUNDAMENTAL DISCOVERIES INTO PRACTICAL TECHNOLOGIES, THE INSTITUTE FOR QUANTUM COMPUTING (IQC) HAS GROWN AND FLOURISHED INTO THE ROBUST, VIBRANT SCIENTIFIC COMMUNITY IT IS TODAY.

Our research is strongly rooted in fundamental science. Nourished by the Quantum Valley ecosystem in Waterloo region, our researchers are translating quantum information concepts into real world applications with widespread, societal impact. We are growing a research industry here that takes the collaboration and the contribution of many brilliant minds. I am proud to see the progress our faculty members, postdoctoral fellows, students, associates and affiliates are making in the field.

The University of Waterloo provides catalytic support through its entrepreneurial environment and strategic academic and industry partnerships needed to move research advances from the lab to the market. The philanthropic support of Mike and Ophelia Lazaridis along with generous federal and provincial funding makes this possible. Canada's Quantum Valley vision is a reality here in Waterloo; it is an exciting time at IQC.

As we move into our 15th year, I reflect on how far we've come. I can't help but look ahead with anticipation for what discoveries are next. Our extraordinary people will continue seeding the way for the next quantum revolution. Thank you to all the individuals and organizations whose support allows IQC to proudly lead the growing quantum technology industry.

Raymond Laflamme
Executive Director
Institute for Quantum Computing
University of Waterloo

AS THE WORLD READIES FOR THE SECOND QUANTUM REVOLUTION, IQC AND ITS PARTNERS IN THE QUANTUM VALLEY PREPARE TO PLAY A LEADERSHIP ROLE

MESSAGE FROM THE BOARD CHAIR

It has been a great year for the advancement of physics and an exciting year in the Quantum Valley.

Around the world, we continue to see large scale investment from governments, research facilities and many of the largest technology companies toward the advancement of physics and the development of new quantum technologies.

In May of this year, Europe announced a new $1 billion euro Flagship program focused on elevating their quantum technology effort. The following is a quote from their "Quantum Manifesto":

> "[T]he second quantum revolution [is] now unfolding worldwide, bringing transformative advances to science, industry and society. It will create new commercial opportunities addressing global challenges, provide strategic capabilities for security and seed as yet unimagined capabilities for the future."

The US Government seems to share this view on the importance of these new quantum technologies as noted in a recent US government report prepared by top US scientists and science policymakers.

IQC and its partners in the Quantum Valley continue to take the necessary steps to enable Waterloo and Canada to play a leadership role in the Second Quantum Revolution and there have been some very exciting advances at IQC over the past year that deserve mention.

Let me start by acknowledging a number of new researchers from around the world that have chosen IQC as the place where they will make their contribution to this exciting field of discovery. Faculty members Vern Paulsen joined IQC in July from the University of Houston; William Slofstra moved from University of California, Davis to Waterloo in August; Wei Tsen joined IQC from Columbia University in January; and Na Young Kim joined IQC from Apple and Stanford University.

Also, we continue to ensure that IQC researchers have access to state-of-the-art labs and equipment including a growing number of cutting edge tools and equipment that have been invented by IQC researchers. In that regard, I am pleased to advise on the completion of the new "Quiet Labs" at the RAC2 facility on the North Campus of the University of Waterloo. The acoustics and vibrations ratings for these labs are so low that they are less than the lowest ratings published by NIST and we believe that these labs are the "quietist" of their kind in the world. We also have started to build the Magnetic Field Lab complete with a 20 Tesla magnet.

The Magnetic Field Lab will be strategically situated beside the Quiet Labs and will enable IQC researchers' ready access to tools that previously could only be accessed by booking appointments at a few US National Labs.

IQC is the result of a strong and longstanding public private partnership with the Government of Canada and the Province of Ontario who have been fundamental partners and investors in IQC since its inception. There is no question that the development of quantum technologies and the commercialization of these technologies in Canada is a national priority. I want to thank both government partners for their continued investment and support for IQC and the Quantum Valley.

In particular, I want to acknowledge the $76 million award to IQC as part of the federal government "Canada First Research Excellence Fund". I have no doubt that the research capability and resources represented by this CFREF funding will bring IQC, the Quantum Valley and Canada a major step closer to establishing ourselves as a global leader in the Second Quantum Revolution.

These things don't just happen. I want to acknowledge the efforts and the contributions by our Founding IQC Director, Raymond Laflamme and that of IQC's deputy director and Principle Investigator for the Transformative Quantum Technologies CFREF program, David Cory. I also wanted to acknowledge the leadership of University President, Feridun Hamdullahpur and his team. Finally, I want to thank the members of the IQC Board of Directors and the IQC Scientific Advisory Committee for their efforts in support of IQC.

The Second Quantum Revolution will change how we view and manipulate matter and energy, manufacture new materials, vastly improve simulation and measurement, computation and communication, data storage and data security, medical diagnostics and medicine and enable advances that would be impossible with even the best classical technologies.

The Second Quantum Revolution promises to create whole new industrial super cycles on the order of the industrial and information revolutions of the past century and the University of Waterloo's investments and strategic focus in Quantum Information Science and Technology will ensure that Canada, its industry and its citizens will benefit.

Sincerely,

Mike Lazaridis, OC, OOnt, FRS, FRSC
Chair, Board of Directors
Institute for Quantum Computing
University of Waterloo

BUILDING ON A FOUNDATION OF EXCELLENCE

MESSAGE FROM THE CHAIR OF THE EXECUTIVE COMMITTEE

Mike Lazaridis had a vision. He saw quantum information science as a budding area of research and recognized the need to transform fundamental discoveries into practical technologies with beneficial impact for our world. He chose the University of Waterloo to set down the roots for the Institute for Quantum Computing, a collaborative, interdisciplinary research environment, to make his vision a reality.

Fourteen years later, IQC is a fundamental part of Waterloo's transformational research plan and its research is leading in an international community of quantum information science and technology research. Over the next five years, IQC's strengths will help propel Waterloo towards a single goal: to be recognized as one of the top innovation universities in the world.

Charting this course is made possible by the collaboration and dedication of many. Thank you to the Faculties of Engineering, Mathematics and Science for your dedication to IQC. Thank you to the fellow members of the executive committee for your expertise and guidance. And thank you, Mike Lazaridis, for your bold, ambitious vision and recognizing the University of Waterloo as the right place to make it happen.

Together, we will build the University of Waterloo as one of the top innovation universities in the world.

George Dixon
Chair, IQC Executive Committee
Vice-President, University Research
University of Waterloo

BUILDING THE QUANTUM VALLEY

THE BREADTH AND QUALITY OF IQC'S RESEARCH INFRASTRUCTURE ALLOWS QUANTUM INFORMATION SCIENCE AND TECHNOLOGY ADVANCEMENT AT THE HIGHEST INTERNATIONAL LEVEL. RESEARCHERS AT IQC COLLABORATE TO HARNESS THE QUANTUM WORLD, REVOLUTIONIZE TECHNOLOGY AND DRIVE FUTURE ECONOMIES. FUNDAMENTAL IDEAS ARE MOVING FROM THE WHITEBOARD INTO THE LAB FOR TESTING, EMERGING AS NEW APPLICATIONS AND ENTERING THE MARKET.

Ultra-powerful computers, unbreakable cryptography, quantum devices, new materials and nanotechnologies of unprecedented efficiencies are some of the discoveries being pioneered at IQC. Together, we are leading the next quantum revolution.

We are building the Quantum Valley.

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 Choi

MATHEMATICS OF QUANTUM INFORMATION
William Sloftsra

NANO-PHOTONICS AND QUANTUM OPTICS LAB
Michal Bajcsy

NANOSCALE MAGNETIC RESONANCE IMAGING LAB
Raffi Budakian

QUANTUM CONTROL AND ERROR CORRECTION
Raymond Laflamme

OPTICAL QUANTUM COMMUNICATION THEORY GROUP
Norbert Lütkenhaus

QUANTUM HACKING LAB
Vadim Makarov

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

QUANTUM MATERIALS AND DEVICES LAB
Wei Tsen

QUANTUM OPTICS AND QUANTUM INFORMATION LAB
Kevin Resch

QUANTUM PHOTONIC DEVICES LAB
Michael Reimer

QUANTUM PHOTONICS LAB
Thomas Jennewein

QUANTUM PROCESSORS LAB
David Cory

QUANTUM-SAFE CRYPTOGRAPHY GROUP
Michele Mosca

QUANTUM SOFTWARE GROUP
Michele Mosca

RELATIVISTIC QUANTUM INFORMATION GROUP
Eduardo Martín-Martínez

SUPERCONDUCTING QUANTUM DEVICES GROUP
Adrian Lupascu

FACULTY

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

FACULTY

Michal Bajcsy
Electrical and Computer Engineering
IQC member since
2014

Jonathan Baugh
Chemistry
IQC member since
2007

Raffi Budakian
Physics and Astronomy
IQC member since
2014

Andrew Childs
Combinatorics and Optimization
IQC member since
2007

Kyung Soo Choi
Physics and Astronomy
IQC member since
2014

Richard Cleve
School of Computer Science
IQC member since
2004

David Cory
Chemistry
IQC member since
2010

Joseph Emerson
Applied Mathematics
IQC member since
2005

Thomas Jennewein
Physics and Astronomy
IQC member since
2009

Na Young Kim
Electrical and Computer Engineering
IQC member since
2016

Raymond Laflamme
Physics and Astronomy
IQC member since
2002

Debbie Leung
Combinatorics and Optimization
IQC member since
2005

Adrian Lupaşcu
Physics and Astronomy
IQC member since
2009

Norbert Lütkenhaus
Physics and Astronomy
IQC member since
2006

Matteo Mariantoni
Physics and Astronomy
IQC member since
2012

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

Michele Mosca
Combinatorics and Optimization
IQC member since
2002

Ashwin Nayak
Combinatorics and Optimization
IQC member since
2002

Vern Paulsen
Pure Mathematics
IQC member since
2015

Michael Reimer
Electrical and Computer Engineering
IQC member since
2015

Kevin Resch
Physics and Astronomy
IQC member since
2006

Wei Tsen
Chemistry
IQC member since
2016

John Watrous
School of Computer Science
IQC member since
2006

Christopher Wilson
Electrical and Computer Engineering
IQC member since
2012

RESEARCH ASSISTANT PROFESSORS

Vadim Makarov
Physics and Astronomy
IQC member since
2012

Eduardo Martín-Martínez
Applied Mathematics
IQC member since
2014

Dmitry Pushin
Physics and Astronomy
IQC member since
2010

William Slofstra
IQC
IQC member since
2015

ATTRACTING WORLD-CLASS PEOPLE

NA YOUNG KIM

NA YOUNG KIM leads the Quantum Innovation (QuIN) laboratory, aiming to build large-scale quantum processors based on novel materials and advanced technologies.

Prior to joining IQC in March 2016, Kim was at Apple Inc., working on the development of small display products. She received a BSc in Physics from Seoul National University and pursued her graduate studies exploring mesoscopic transport properties in low-dimensional nanostructures in the Department of Applied Physics at Stanford University. During her postgraduate research, she expanded her scope to the fields of quantum optics and nanophotonics, working on several experimental and theoretical projects. She attended the Quantum Innovators workshop at IQC in 2014.

WEI TSEN

WEI TSEN completed his PhD in Applied Physics at Cornell University under the guidance of Jiwoong Park. He then joined the Department of Physics at Columbia University as a postdoctoral associate with **ABHAY PASUPATHY** and **PHILIP KIM**, where he studied atomically thin quantum materials and incorporated them in nanoscale electronic devices.

Tsen has continued to explore these materials and develop novel quantum devices based on their exotic properties. After attending Quantum Innovators in 2015, he joined IQC and the Department of Chemistry at the University of Waterloo as an assistant professor in January 2016.

VERN PAULSEN

VERN PAULSEN joined the University of Waterloo as a professor in the Faculty of Mathematics and as a faculty member of IQC in July 2015. He received his PhD in Mathematics from the University of Michigan, Ann Arbor. Prior to joining IQC, Paulsen was a John and Rebecca Moores professor at the University of Houston.

Paulsen's mathematical research explores quantum information theory. He has been involved in Quantum Information Technology (QIT) programmes at Sweden's Mittag-Leffler Institute and Cambridge's Isaac Newton Institute. His research has resulted in over 100 research articles. He has written four graduate level textbooks in mathematics and won several teaching awards.

WILLIAM SLOFSTRA

WILLIAM SLOFSTRA received his PhD in Mathematics from the University of California, Berkeley in 2011. After spending part of 2012 at the University of British Columbia as a Research Associate, Slofstra returned to California as the Krener Assistant Professor at the University of California, Davis. Slofstra moved to the University of Waterloo in August 2015 as a Research Assistant Professor at IQC.

His research interests have focused on algebra, specifically in Lie theory/ representation theory, Schubert calculus and connected areas, as well as non-local games.

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 ARE LAYING THE GROUNDWORK FOR EXCITING FUTURE DEVELOPMENTS.

NATIONAL & INTERNATIONAL AGREEMENTS

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

INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE
Quebec

INSTITUT TRANSDISCIPLINAIRE D'INFORMATION QUANTIQUE
Quebec

TSINGHUA UNIVERSITY
China

UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA
China

RAMAN RESEARCH INSTITUTE
India

TECHNION – ISRAEL INSTITUTE OF TECHNOLOGY
Israel

KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY
Korea

DELFT TECHNICAL UNIVERSITY
The Netherlands

CENTRE FOR QUANTUM TECHNOLOGIES
Singapore

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:

UNIVERSITÄT INNSBRUCK
Austria

ÉCOLE NORMALE SUPÉRIEURE DE LYON
France

UNIVERSITÉ PARIS DIDEROT
France

FRIEDRICH-ALEXANDER-UNIVERSITÄT ERLANGEN-NÜRNBERG
Germany

UNIVERSITÄT DES SAARLANDES
Germany

UNIVERSITY OF LATVIA
Latvia

DELFT TECHNICAL UNIVERSITY
The Netherlands

NATIONAL UNIVERSITY OF SINGAPORE
Singapore

IN 2015-2016, IQC RESEARCHERS:

- COLLABORATED with **485** researchers from **108** institutions in **26** countries
- PARTICIPATED in **140** external conferences
- WELCOMED **157** scientific visitors from **94** leading institutions and **360** conference attendees to exchange ideas and research in quantum information.

AFFILIATES AND ASSOCIATES

AN INTERDISCIPLINARY APPROACH

IQC affiliate and associate **BEI ZENG**'s theoretical research aims to construct a class of quantum-error correcting codes to achieve reliable transmission and processing of quantum information by a quantum computer. With degrees in both physics and mathematics from Tsinghua University and the Massachusetts Institute of Technology (MIT), Zeng values an interdisciplinary approach to quantum information research: "In this field, one person cannot be an expert in everything; collaboration is a useful tool."

Zeng first joined IQC in 2009 as a postdoctoral fellow, working with supervisors **ASHWIN NAYAK** and **JOHN WATROUS**. Now an associate professor in the Department of Mathematics and Statistics at the University of Guelph, Zeng's affiliation with IQC keeps her connected to the institute and the channels open for collaborative research. She has explored quantum cryptography with **NORBERT LÜTKENHAUS** and bridged theoretical concepts for experimental testing with **RAYMOND LAFLAMME** and **KEVIN RESCH**.

Currently, Zeng is working on the first-of-its-kind textbook that introduces the application of quantum information science to the study of condensed matter physics. The textbook is a collaboration with researchers from the California Institute of Technology, the Chinese Academy of Sciences and Massachusetts Institute of Technology. It will be published as part of a Quantum Science and Technology book series with Springer.

UNDERSTANDING THE QUANTUM WORLD

"Designing a quantum computer provides a means to explore deeper aspects of quantum theory," says **SHOHINI GHOSE**, IQC affiliate and Professor in the Department of Physics and Computer Science at Wilfrid Laurier University. "Achieving the realization of a quantum computer would also mean a better understanding of the quantum world."

When Ghose joined Laurier in 2005, she saw IQC as a nearby hub for quantum research. She was appointed an affiliate member at IQC and an adjunct professor in the University of Waterloo's Department of Physics and Astronomy. Ghose co-supervises IQC PhD student **MEENU KUMARI**, who is working on a joint project with Research Assistant Professor **EDUARDO MARTÍN-MARTÍNEZ** and IQC associate **ACHIM KEMPF**.

"Discussing quantum information science with other researchers leads to new ideas; this is how research progresses," Ghose said. Her research in quantum information science focuses on quantum chaos and multi-partite entanglement. She is investigating how to use entanglement as a resource for quantum information, in particular for controlled teleportation and large-scale network entanglement that could lead to the development of a quantum internet.

WOMEN IN PHYSICS

When Ghose faces a research challenge, she considers established evidence, finds required expertise and then proceeds with a clear plan of attack. She approaches the under-representation and participation of women in physics and science research fields the same way. As founding Director of the Centre for Women in Science at Wilfrid Laurier University, Ghose is building "a strong community for women in science through research, communication and action."

ACADEMIC & SCIENTIFIC VISITORS

APRIL 1, 2015 TO MARCH 31, 2016

Scott Aaronson, Massachusetts Institute of Technology
Alvaro Martin Alhambra, University College London
Dimitrios Antsos, National Aeronautics and Space Administration Headquarters
Bhashyam Balaji, Government of Canada
Jean-Daniel Bancal, University of Michigan
Ben Baragiola, University of New Mexico
Howard Barnum, University of New Mexico
Tim J. Bartley, National Institute of Standards and Technology
Stefi Baum, University of Manitoba
Stefanie Beale, Acadia University
Shalev Ben-David, Massachusetts Institute of Technology
Mario Berta, California Institute of Technology
Jean-François Biasse, University of South Florida
Immanuel Bloch, Max Planck Institute of Quantum Optics
Boris Braverman, Massachusetts Institute of Technology
Harry Buhrman, University of Amsterdam
Brandon Buonacorsi, University of California, Davis
Tommaso Calarco, Ulm University
Edward Chen, Massachusetts Institute of Technology
Lily Chen, National Institute of Standards and Technology
Nai-Hui Chia, Pennsylvania State University
Shen Chiu, Government of Canada
Franklin Cho, University of Southern California
Jerry Chow, IBM Research
Ethan Clements, Miami University
Xingshan Cui, University of California, Santa Barbara
Anthony Damini, Government of Canada
Tal David, Defence Research and Development, Israel
Ying Dong, Hangzhou Normal University
Helen Fay Dowker, Imperial College London
Chris Erven, University of Bristol
Chris Ferrie, The University of Sydney
Karsten Flensberg, Niels Bohr Institute, University of Copehnhagen
Fabian Furrer, NTT Basic Research Laboratories
Dorian Gangloff, Massachusetts Institute of Technology
Ankit Garg, Princeton University
Barry Geldzahler, National Aeronautics and Space Administration Headquarters
Sevag Gharibian, University of California, Berkeley
Goh Koon Tong, Centre for Quantum Technologies
Chris Granade, The University of Sydney
Markus Grassl, Max Planck Institute for the Science of Light
Mary Hockaday, Los Alamos National Laboratory
Andreas Hülsing, Eindhoven University of Technology
K. Rajibul Islam, Massachusetts Institute of Technology
Nitin Jain, Northwestern University
Hamid Javadi, National Aeronautics and Space Administration Headquarters
Stacey Jeffery, California Institute of Technology
Sajeev John, University of Toronto
Archana Kamal, Massachusetts Institute of Technology
Phil Kaye, Government of Canada
Viv Kendon, Joint Quantum Centre
Nathan Killoran, Ulm University
Na Young Kim, Stanford University
Piotr Kolenderski, Nicolaus Copernicus University
Robin Kothari, Massachusetts Institute of Technology
Aleksander Kubica, California Institute of Technology
Paul Kwiat, University of Illinois at Urbana-Champaign
Catherine Laflamme, University of Innsbruck
Eric Larson, University of Michigan
Minsoo Lee, Korea Institute of Science and Technology
Gaby Lenhart, European Telecommunications Standards Institute
Joshua Levin, Boston University
Junan Lin, McGill University
Jorma Louko, University of Nottingham
Xiaodong Ma, University of Science and Technology
Dirk van der Marel, University of Geneva
John Martinis, University of California, Santa Barbara
Serge Massar, Université libre de Bruxelles
Christian Mastromattei, Queen's University
Matthew McKague, University of Otago
Igor Mekhov, University of Oxford
Piotr Migdal, The Institute of Photonic Sciences
Carl Miller, University of Michigan
Rajat Mittal, Indian Institute of Technology, Kanpar
András Molnár, Max Planck Institute of Quantum Optics
Christopher Monroe, University of Maryland
Dana Moshkovitz, Massachusetts Institute of Technology
Yasunobu Nakamura, University of Tokyo
Matthieu Nannini, McGill University
Tracy Northup, University of Innsbruck
Ibrahim Nsanzineza, Syracuse University
Gerardo Ortiz, Indiana University Bloomington
Juliana Park, Seoul National University
Hakop Pashayan, The University of Sydney
Raj Patel, Griffith University
William Paul, IBM Research
Mark Paulsen, Canadian Imperial Bank of Commerce
Corsin Pfister, Centre for Quantum Technologies
Marco Piani, University of Strathclyde, Glasgow
Michele Piscitelli, Royal Holloway, University of London
Liam Pleven, The Wall Street Journal
Britton Plourde, University of Syracuse
Marzio Pozzuoli, Ryerson University
Kathy Prestridge, Los Alamos National Laboratory
Hao Qin, Télécom ParisTech
Sadegh Raeisi, Friedrich-Alexander Universität Erlangen-Nürnberg
Cosmic Raj, Tata Institute of Fundamental Research
Bertrand Reulet, Universié de Sherbrooke
Pablo Rodriguez-López, Laboratoire de Physique Théorique et Modèles Statistiques
Joseph Salfi, University of New South Wales
Valerio Scarani, Centre for Quantum Technologies
Crystal Senko, Harvard University
Pascale Sevigny, Government of Canada
Si-Hui Tan, Singapore University of Technology and Design
Jamie Sikora, Centre for Quantum Technologies
Christoph Simon, University of Calgary
Ajit Singh, Indian National Science Academy
Urbasi Sinha, Raman Research Institute
Daniel Terno, Macquarie University
Wei Tsen, Columbia University
Mukund Vengalattore, Cornell University
Sebastian Verschoor, Eindhoven University of Technology
Cameron Vickers, University of Connecticut
Saeqa Vrtilek, Harvard University
Frank Wilhelm-Mauch, Saarland Univeristy
Aye Lu Win, Old Dominion University, USA
Erik Woodhead, The Institute of Photonic Sciences
Xingyao Wu, University of Michigan
Ben Yager, Royal Holloway, University of London
Dong Yang, University of Barcelona
Badri Younes, National Aeronautics and Space Administration Headquarters
Nan Yu, National Aeronautics and Space Administration Headquarters
Anton Zeilinger, University of Vienna
Heping Zeng, East China Normal University
Jingfu Zhang, Technische Universität Dortmund

LONG-TERM VISITORS

APRIL 1, 2015 TO MARCH 31, 2016

Vineeth S. Bhaskara, Indian Institute of Technology Guwahati
Mitchell Brickson, Goshen College
Lu Cong, East China Jiao Tong University
Matthew Coudron, Massachusetts Institute of Technology
Emilie Mai Elkiaer, University of Copenhagen
Juan Carlos García Escartín, Universidad de Valladolid
Luis Garay, Universidad Complutense de Madrid
Cheng Guo, Tsinghua University, University of Technology Sydney
Markos Karasamanis, University College London
Thomas Kauten, University of Innsbruck
Shun Kawakami, The University of Tokyo
Linghang Kong, Tsinghua University
Tony Leggett, University of Illinois at Urbana-Champaign
Keren Li, Tsinghua University
Fen Liu, East China Jiaotong University
Zhengfang Liu, East China Jiaotong University
Benjamin Lovitz, Bates College
Lyu Ming, Tsinghua University
Morgan Mastrovich, Harvey Mudd College, Claremont California
Laura Córdova Matte, Pontifical Catholic University of Rio Grande do Sul
Eric Metodiev, Harvard University
Dominique Pouliot, University of Illinois at Urbana-Champaign
Yihui Quek, Massachusetts Institute of Technology
Fred Shultz, Wellesley College
Frederick Strauch, Williams College
Aarthi Sundaram, Centre for Quantum Technologies, National University of Singapore
Jonathan Vandermause, Dartmouth College
Qingping Wu, East China Jiaotong University
Qian Xue, Qingdao University
Chan Ho Yoon, Columbia University

A ROYAL VISIT

On May 28, the University of Waterloo welcomed the King and Queen of the Netherlands. Their Majesties **KING WILLEM-ALEXANDER** and **QUEEN MÁXIMA** signed two memoranda of understanding: the first, with the University of Waterloo and Delft University of Technology, and secondly with the Region of Waterloo and the Brainport Eindhoven Region.

The King and Queen also announced the Liberation Scholarship program in celebration of the 70th anniversary of the liberation of the Netherlands during the Second World War. IQC Master's student **MADELAINE LIDDY** was among the first of 70 Canadians who received the Liberation Scholarship. Studying under **DAVID CORY**, Canada Excellence Research Chair in Quantum Information Processing, Liddy is researching Nitrogen-Vacancy (NV) chemical sensors.

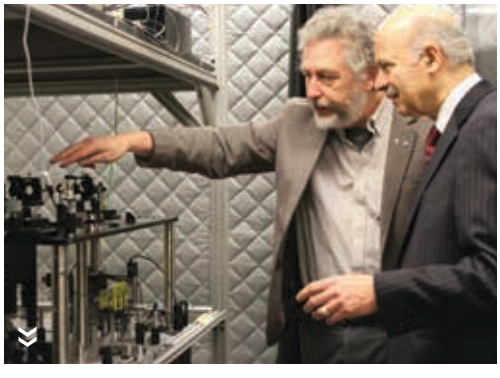
TOURING QUANTUM VALLEY

AS PART OF THE ENTREPRENEURIAL ENVIRONMENT AT THE UNIVERSITY OF WATERLOO, IQC PLAYS A CONTRIBUTING ROLE IN WATERLOO REGION'S RICH ECOSYSTEM OF DISCOVERY AND TECHNOLOGY GROWTH. MOVING INDUSTRY FORWARD HAPPENS BY SHARING FUNDAMENTAL SCIENTIFIC DISCOVERIES; IQC IS BUILDING PARTNERSHIPS AND SHOWING QUANTUM SCIENCE TO QUANTUM VALLEY VISITORS.

Delegates from Finance Canada came to IQC during a tour of Waterloo Region on September 30. At IQC, **RICHARD BOTHAM**, Assistant Deputy Minister from the Economic and Fiscal Policy Branch along with representatives from the Microeconomic Policy Analysis Division including **SOREN HALVERSON**, **EVELYN DANCEY** and **EVA AUDY** saw the Quantum NanoFab and toured the labs at RAC II.

BILL MANTEL, Assistant Deputy Minister from the Ontario Minister of Research and Innovation and his group visited the Quantum NanoFab and the RAC 2 labs at IQC on October 7.

On January 17, members of the federal government met with IQC members and were given a tour of the facilities. The delegation included the Honourable **NAVDEEP BAINS**, Minister of Innovation, Science and Economic Development, the Honourable **BARDISH CHAGGER**, Minister of Small Business and Tourism, and MPs **RAJ SAINI** and **MARWAN TABBARA** of the Kitchener Centre and Kitchener South-Hespeler districts respectively.



The Honourable **REZA MORIDI**, Minister of Research and Innovation and Minister of Training, Colleges, and Universities, visited IQC January 25 to become acquainted with the researchers and their work.

March 2, **KIRSTY DUNCAN**, Minister of Science and members of the department of Innovation, Science and Economic Development (ISED) Canada visited the Quantum NanoFab and researcher **KEVIN RESCH**'s lab to learn about the research done at IQC.

JOHN TORY, Mayor of Toronto, **DAVE JAWORSKY**, Mayor of Waterloo, and **BERRY VRBANOVIC**, Mayor of Kitchener toured the labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre on March 23. The visit was part of a larger effort to promote the Toronto-Waterloo 'innovation corridor'.

FROM THEORY TO EXPERIMENT

FACULTY MEMBER **NORBERT LÜTKENHAUS** MAKES CONNECTIONS BETWEEN ABSTRACT THEORY AND EXPERIMENTAL IMPLEMENTATION. HE STARTED EXPLORING THEORETICAL CONCEPTS, THE BASIC LAWS OF PHYSICS AND THE FUNDAMENTAL STRUCTURES OF QUANTUM MECHANICS, WHILE CONSIDERING WHAT CAN ACTUALLY BE REALIZED IN A LAB SETTING DURING HIS PhD RESEARCH AT THE UNIVERSITY OF STRATHCLYDE IN SCOTLAND – AND HASN'T LOOKED BACK SINCE.

TRANSLATING A QUANTUM ADVANTAGE

Now, as a professor at IQC and the Department of Physics and Astronomy at the University of Waterloo, his research focuses on finding advantageous quantum communication protocols. Lütkenhaus and the Optical Quantum Communication Theory Group act as translators, bridging the gap at the interface between a theoretical computer sciences-based approach to quantum communication and its physical implementation.

TOOLS FOR QUALITY

A pioneer in the field of quantum communication, Lütkenhaus has been studying Quantum Key Distribution (QKD) for more than two decades. QKD protocols allow secure communication between two parties, Alice and Bob, who establish a shared secret key by exchanging photons. If an eavesdropper (Eve) attempts to intercept the key, Alice and Bob detect the disturbance. If there is no disturbance, the security of their shared key is guaranteed. QKD relies on the properties of quantum mechanics; this provides a quality of advantage over classical communication methods since the establishment of keys cannot be accomplished by classical physics.

However, the challenge is to calculate the theoretical allowed length of the secret key and the experimentally observed distance for any given protocol.

Recently, postdoctoral fellow **PATRICK COLES**, undergraduate research assistant **ERIC METODIEV** and Lütkenhaus developed the first available MATLAB software program to evaluate the security of any QKD protocol. The software program completes the security evaluation, giving researchers more time for exploring new QKD protocols and implementations. They have plans to introduce a guide for users – other researchers who will use this tool – on how to enter the data using a new protocol into the software.

TOOLS FOR QUANTITY

Communication complexity explores certain problems where using quantum mechanics provides a quantitative advantage – using fewer resources or improving efficiency – compared to solving the same problem classically. "There are some communication tasks that show an exponential advantage theoretically if we use quantum mechanics instead of classical physics, which is a very exciting prospect," explained Lütkenhaus. "The challenge is to find an implementation to realize the advantage."

This is another area where Lütkenhaus is translating theory into practical implementation, considering current tools and technology. "We look at the heart of the protocol and propose something simpler for experimental implementation, something that will have the same effect but is more accessible for experimentalists." Using this approach, Lütkenhaus and collaborators used laser pulses, a standard tool in optical communication, in place of complicated signal structures to perform a communication protocol.

FUNDAMENTAL RESEARCH FUELS SOLUTIONS

Progress is promising, but there's still more work to do. "It's important to explore basic research at the fundamental level," said Lütkenhaus. "Fundamental research will not happen on its own, we need to make it happen. The applications, though, will emerge from fundamental research."

WEB

Numerical approach for unstructured quantum key distribution
http://bit.ly/numerical-QKD

THE EVOLUTION OF evolutionQ

Quantum technologies are rapidly evolving. The ability to disrupt traditional cybersecurity methods poses serious risk to the confidentiality of information. **NORBERT LÜTKENHAUS** and **MICHELE MOSCA** saw a need for quantum-safe solutions. Their joint expertise in Quantum Key Distribution (QKD) and conventional quantum-safe cryptography is the perfect mix for bringing quantum-safe cybersecurity solutions into the market.

Lütkenhaus and Mosca launched *evolutionQ* in 2015, a startup that provides organizations with quantum-safe solutions to protect their data and information technology infrastructure from future quantum attacks. "We saw that companies were looking for full-package solutions in this space," said Lütkenhaus. "That is something that we can offer with our knowledge of the quantum-safe scene."

He also sees *evolutionQ* as a landing spot for graduate students and postdoctoral fellows who choose to move from academia to a career in industry. "We are building a workforce. The need is clearly there and will continue to grow," notes Lütkenhaus.

THE QUANTUM NEUTRON

THE PERFECT CRYSTAL NEUTRON INTERFEROMETER MEASURES ONLY 10 TO 15 CENTIMETRES IN LENGTH, BUT IT IS A POWERFUL DEVICE THAT MEASURES FORCES OF NATURE SUCH AS GRAVITY, NUCLEAR AND ELECTROMAGNETIC INTERACTIONS. NEUTRONS ARE MASSIVE, SUBATOMIC, ELECTRICALLY NEUTRAL PARTICLES THAT CARRY SPIN AND HAVE UNIQUE PENETRATING ABILITIES – PROPERTIES THAT MAKE NEUTRONS USEFUL FOR PROBING ALL TYPES OF MATTER.

Research Assistant Professor **DMITRY PUSHIN** is using neutron interferometry to study quantum information science. His neutron source is a nuclear reactor at the National Institute for Standards and Technology (NIST) Center for Neutron Research (NCNR) in Maryland, United States; one of only two facilities in the world currently working with perfect crystal neutron interferometers.

The source sends a beam of neutrons into the interferometer. The interferometer creates two separate paths that cross and mix at the exit, so the neutron can travel through both paths at the same time. In other words, the neutron's wavefunction can be described as a coherent superposition of the two interferometer paths, which allows neutrons to self-interfere and reveals a measureable quantum phase due to the neutron's interaction with forces and materials.

"Neutrons are a unique tool," said Pushin. "We are using neutrons and neutron interferometry to develop new technologies, study new materials and improve our understanding of the world."

BUILDING A RESEARCH DEVICE

Initially, the sensitivity of the interferometer required a massive vibration isolation system to prevent interference from any kind of environmental disturbances, including passers-by and even subtle temperature changes. Using quantum algorithms, Pushin proposed a new design to make the interferometer less sensitive to vibrations. Now, the improved decoherence-free subspace neutron interferometer sits on a standard optical table and is closer to the neutron source, increasing the number of neutrons that flow into the device at once, called the neutron flux.

EXPLORING MATERIALS

Recently, Pushin led an experiment to test the concept of controlling neutron orbital angular momentum (OAM). This control of OAM can reveal magnetic properties of materials, as well as provide a more sensitive probe of superconducting and chiral materials.

The quantum control of neutrons is also promising for the study and engineering of quantum materials. IQC faculty member **GUO-XING MIAO** is developing new topological insulator materials for quantum information processing. Pushin is working with Miao to use interferometry techniques to characterize and improve the quantum stability of new materials that Miao is growing in his lab.

PROBING FUNDAMENTAL SCIENCE

Quantum theory is the focus of a second collaboration with IQC faculty member **JOSEPH EMERSON**. Neutrons can probe fundamental aspects of quantum mechanics, deepening our understanding of the universe. Pushin is using neutron interferometry to test the linearity of quantum mechanics. Similar experiments have been conducted using photons; neutrons offer a new method of measurement that is not limited by the same type of errors.

TALKING THE SAME LANGUAGE

Pushin's collaborations span across different fields of physics, from fundamental to applied research. "We may be using different research tools, but we are using the same language to communicate. We see the same effect described by a mathematical language," Pushin said. "It's the same physics, same language, but with a completely different experimental setup."

Tools for neutron interferometry research are about to become more accessible. Pushin is leading the experiments at a new neutron interferometry beam line at NCNR. Pushin is excited about future research possibilities: "Opening this facility for researchers and companies will open the doors to novel neutron interferometry research and applications."

WEB *Controlling neutron orbital angular momentum*
http://bit.ly/neutron-oam

SEARCHING FOR NEUTRINOS:

ADVANCING TECHNOLOGY FOR FUNDAMENTAL DISCOVERIES

DMITRY PUSHIN is one of 68 scientists and engineers from 10 universities and four national laboratories collaborating to build a first-of-its-kind, short detection device for the Precision Oscillation and Spectrum Experiment (PROSPECT), a project funded by a $3 million grant from the U.S. Department of Energy.

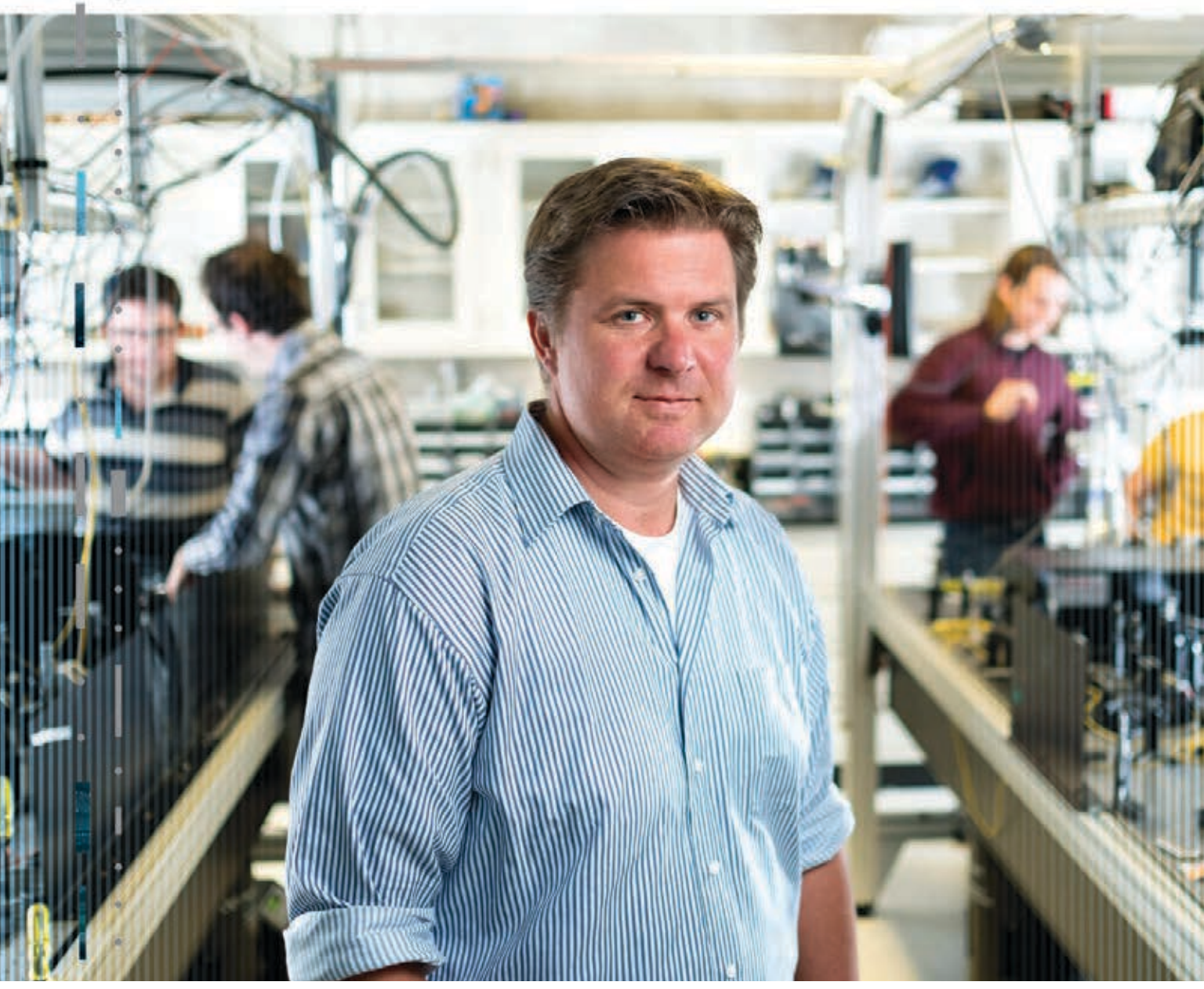
The detection instrument will have unparalleled sensitivity to study the energy distribution of neutrinos, subatomic particles that move through the universe with almost no mass and no electrical charge. Studying the properties and the behaviour of neutrinos may unlock the answers to fundamental questions about the nature of matter in the universe.

BUILDING NEXT GENERATION DEVICES

NEUTRON OPTICS BUILDS COMPONENTS FOR NEXT GENERATION NEUTRON DEVICES FOR MATERIAL STUDIES. IN PARTICULAR, IT PROVIDES COMPONENTS FOR NEUTRON INTERFEROMETRY.

PUTTING THEORY TO THE TEST ONE PHOTON AT A TIME

SEEING IS BELIEVING FOR IQC AND DEPARTMENT OF PHYSICS AND ASTRONOMY FACULTY MEMBER **KEVIN RESCH**, DEPUTY DIRECTOR, ACADEMIC. HIS NATURAL CURIOSITY ABOUT INTERACTIONS BETWEEN LIGHT AND MATTER AT THE QUANTUM LEVEL DREW HIM TOWARDS EXPERIMENTAL RESEARCH IN QUANTUM OPTICS, THE STUDY OF LIGHT PHENOMENA THAT CANNOT BE EXPLAINED BY CLASSICAL PHYSICS.



TOOLS OF THE TRADE

Resch's lab is outfitted with a collection of tools used for designing and implementing optics experiments to explore the quantum realm. Most experiments begin with a laser, either continuous or pulsed, depending on the particular application. Other tools anchored to large optics tables include: mirrors for directing laser beams; nonlinear optical crystals that create entangled photons or allow different light beams to interact; half- and quarter-wave plates for manipulating photon polarization; sensitive detectors for measuring single photons; and spectrometers for characterizing their spectra.

Investigating the fundamental principles of quantum mechanics, Resch, Canada Research Chair in Optical Quantum Technologies, uses these tools to test physical theories and probe the basic ideas of quantum information science.

DETECTING QUANTUMNESS IN THE LAB

Noncontextual models assume that systems have definite properties and that two systems that are identical, as far as any experiment could tell, must have the same set of properties. It turns out that these seemingly reasonable assumptions are at odds with quantum mechanics; at least one of the theories must be wrong.

Until recently, it was not feasible to test the concept of noncontextuality in a lab as the theoretical assumptions did not allow for any experimental imperfections. IQC affiliate **ROB SPEKKENS**, a faculty member at the Perimeter Institute for Theoretical Physics (PI) and the Department of Physics and Astronomy at the University of Waterloo, studies quantum foundations, exploring the concepts and mathematics of quantum theory. Spekkens, along with PI postdoctoral researcher **MATTHEW PUSEY** and **RAVI KUNJWAL** from The Institute of Mathematical Sciences, India, lifted the theoretical limitations and proposed an experiment that could test for noncontexuality, taking the realities of experiment into account.

Resch and his research group put the improved theory to the test. IQC PhD student **MICHAEL MAZUREK** constructed the experimental setup out of single photon emitters and detectors. "We found a failure of noncontextuality, without experimentally unachievable theoretical assumptions," said Resch. "Violation of noncontextuality as a witness of quantumness could have widespread applicability, even broader than the well-known Bell's inequality violation."

Determining how the universe is quantum at the fundamental level helps researchers understand how quantum mechanics can be used for applications such as quantum cryptography and quantum computing. By continuing to make advances in fundamental research, Resch's research group helps shorten the lead-time to advances in devices and technologies.

WEB

An experimental test of noncontextuality without unphysical idealizations
http://bit.ly/exp-noncontextuality

STARTING WITH AN IDEA

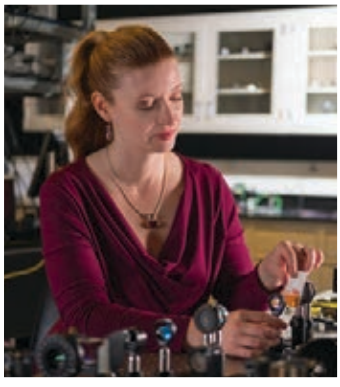
Often a single conversation is all it takes to spur an idea. A brief chat at a conference in 2012 was the beginning of collaborative research between **KEVIN RESCH** and **BEN SUSSMAN**, Research Officer at the National Research Council of Canada (NRC).

Sussman's research group at NRC was working with diamond as a type of quantum memory by storing a pulse of light, or a vibration, in a regular diamond lattice. The first idea was to replace the laser with a single photon source to see if the photon can be stored and retrieved from the diamond and maintain its quantum properties. IQC PhD students **KENT FISHER** and **JEAN-PHILIPPE MacLEAN** built the photon source for the experiment. The experiment was successful in demonstrating the storage and retrieval of a photon in the diamond quantum memory, promising to be a possible light-matter interface for quantum processing applications.

After bringing the IQC and NRC research groups together for the first project, more ideas hatched and the research continues. In a complementary experiment, the researchers showed that once a photon was driven into the diamond for storage by a laser, retrieving the photon using a second laser tuned to a different frequency changed the photon's colour and bandwidth. "Changing the colour of a stored photon is useful for frequency or wavelength multiplexing, a technique that is used in communications today," said Fisher.

"It's great to see the research take a natural direction from our groups working together to solve problems," said Resch. "Sharing ideas and resources is how research breakthroughs will happen."

THE TURBULENCE EFFECT



AT JUST 15, **KATANYA KUNTZ** STARTED EXPLORING THE PHYSICS LABS AT THE UNIVERSITY OF CALGARY AND MEETING WEEKLY WITH **DAVID FRY**, WHO WAS A PROFESSOR IN THE DEPARTMENT OF PHYSICS AND ASTRONOMY. THROUGH A DISTANCE-LEARNING CURRICULUM IN GRADE 10, SHE TOOK ON INDEPENDENT PROJECTS TO EXPLORE CONCEPTS SHE WAS CURIOUS ABOUT. ONE EARLY PROJECT WAS INVESTIGATING THE ZEEMAN EFFECT, CAUSED WHEN AN ATOM IS SUBJECTED TO A MAGNETIC FIELD, WHICH SPLITS ITS SPECTRAL LINES INTO MULTIPLE COMPONENTS. KUNTZ WAS LEARNING ABOUT THE QUANTUM MECHANICAL STRUCTURE OF AN ATOM BEFORE SHE HAD EVEN TAKEN A SENIOR LEVEL HIGH SCHOOL PHYSICS COURSE.

Her passion for physics has taken her across the world. At the University of New South Wales in Canberra, Australia, Kuntz generated quantum resource states for quantum communication as part of her PhD thesis. Now as a postdoctoral fellow at IQC, Kuntz continues research in quantum communication, investigating how atmospheric turbulence plays a role in secure Quantum Key Distribution (QKD).

TWINKLING TURBULENCE

The thicker the atmosphere, the more stars appear to twinkle. Air currents flying around in the atmosphere interfere constructively and destructively with beams of starlight, causing the light to reach our eyes at different times. The turbulent interaction between the atmosphere and light creates the twinkling star effect.

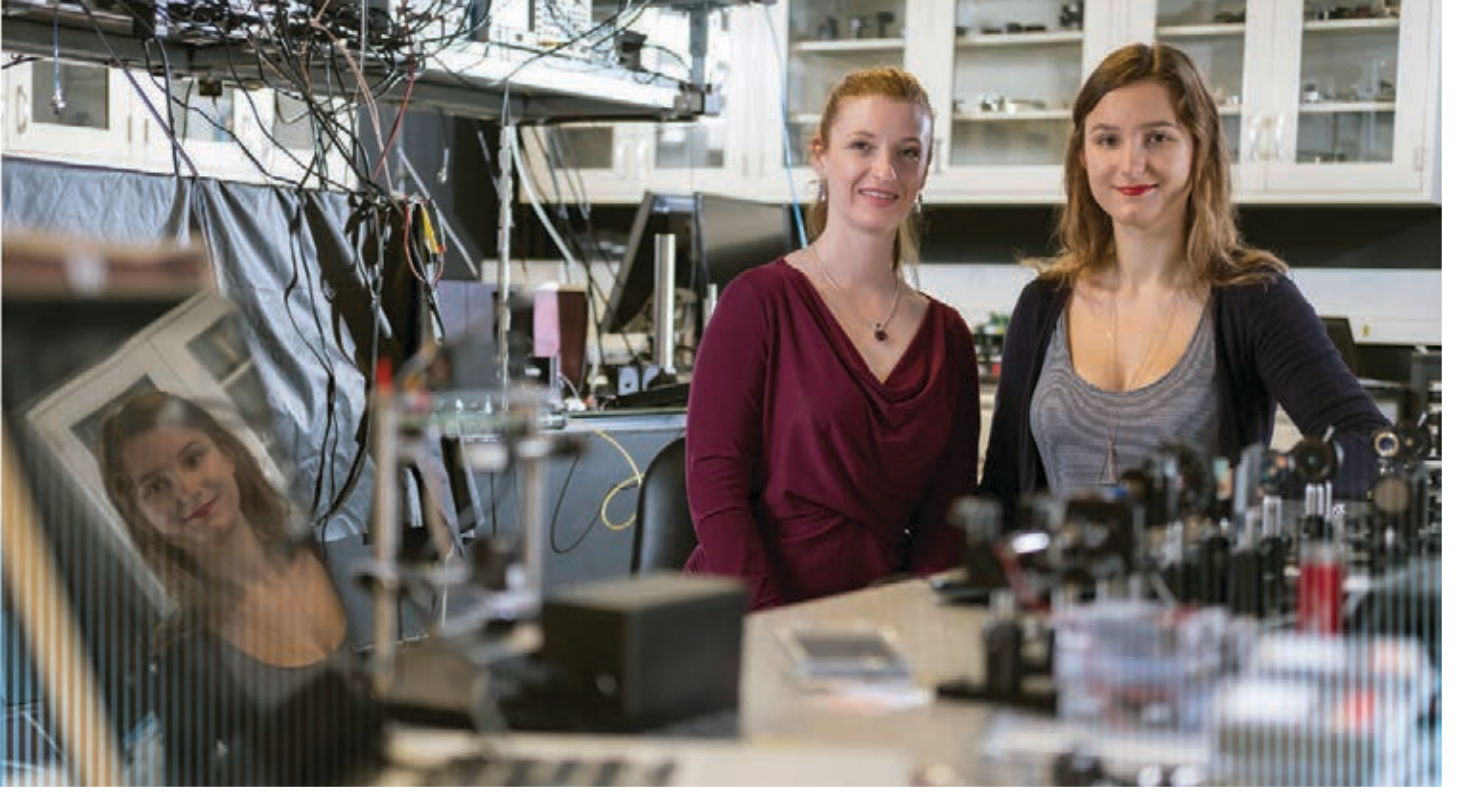
Kuntz is simulating atmospheric turbulence in the lab to test the security of QKD protocols. When a laser beam hits a small reflective device called a spatial light modulator (SLM), the SLM imparts a phase shift on the light that simulates a beam travelling through turbulence. Turbulence causes a laser beam to bounce around, similar to the twinkling star effect. In collaboration with **THOMAS JENNEWEIN** and **VADIM MAKAROV**, Kuntz is searching for the level of turbulence that will prevent hacking and ensure secure QKD.

An eavesdropper, Eve, may try to hack the QKD receiver to learn about the secret key being shared. The precise angle Eve needs to send her beam to hack the system may be compromised by atmospheric turbulence. Turbulence causes a smearing or scattering effect on the light that inhibits Eve's ability to hack the communication.

"Once we find the bound where the strength of turbulence makes the receiver unhackable, the next step is to test it outside," said Kuntz. Determining this bound will give QKD users more information about the minimum safe zone necessary for safe communication. For example, a naval fleet can secure a perimeter around each ship, and know for certain they can exchange a secret key based on the level of atmospheric turbulence present.

HOOKED ON QUANTUM PHYSICS

Before the QKD device is ready to test with real world atmospheric turbulence, further simulation is required. Kuntz readily takes on this mission, fueled by her passion for physics and continuous learning. She acknowledges the positive impact that strong scientific role models, including Fry, have had on her academic career. Kuntz hopes that she can play the same mentorship role for others. "When I am working with a student, I aim to improve their confidence," said Kuntz. "I think we should stop stereotyping physics and math as hard, and encourage kids to get involved in science at a young age."



EXPANDING KNOWLEDGE

NATURALLY CURIOUS, **KAYLA HARDIE** LOVES LEARNING. UNCOVERING NOVEL IDEAS AND UNDERSTANDING HOW THE UNIVERSE WORKS FASCINATES HER. IT'S ONE OF THE REASONS SHE APPROACHED IQC FACULTY MEMBER **THOMAS JENNEWEIN** IN HER FIRST YEAR AT UNIVERSITY FOR A MEANINGFUL WORK EXPERIENCE THAT WOULD ENHANCE HER ACADEMIC CAREER WHILE SEARCHING FOR A PART-TIME JOB.

"He was open-minded about what I could do, even though I was a first-year student," said Hardie. She jumped right in as an Undergraduate Research Assistant working with Jennewein's research group, which focuses on long-distance quantum communication.

CHARACTERIZING OPTICAL COATINGS

In an optics lab like Jennewein's, there is usually a collection of miscellaneous optics, like mirrors and lenses, many with different types of coatings. These filters or anti-reflection coatings alter the way light is transmitted or reflected for particular wavelengths, but they are often missing labels or degrade over time. To characterize the optical coatings in an efficient and reliable manner, Hardie built a useful laboratory tool that performs the task: a light emitting diode (LED)-based spectrophotometer.

A microcontroller that rotates a board with 10 LEDs over an optical sample runs the device. A silicon photodetector measures the light transmitted through each LED, identifying the optical coating of the sample based on the amount of light that gets through. The device could make an excellent teaching tool in the classroom and is an affordable alternative to commercial-grade spectrophotometers, essential for use in the lab.

"Everyday I faced a new learning curve in the lab," said Hardie. "I was part of the full cycle – from the initial idea, to building the device, and writing and submitting the paper." Along with Jennewein, collaborators on the paper *Inexpensive LED-based spectrophotometer for analyzing optical coatings* include PhD student **SASCHA AGNE** and postdoctoral fellow **KATANYA KUNTZ**.

Now entering her third year studying physics at the University of Waterloo, Hardie is positive that her future will include research in some respect. Her experience at IQC has prepared her for that. She also wants to keep on learning. "Expanding my knowledge helps me gain a better perspective on life. It's just about living a fuller life."

THE SCIENTIFIC LEADERS OF TOMORROW

QUANTUM INFORMATION SCIENCE HAS THE POTENTIAL TO LEAD TO TRANSFORMATIVE TECHNOLOGICAL ADVANCEMENTS AND A DEEPER UNDERSTANDING OF THE PHYSICAL WORLD IN WHICH WE EXIST. THE QUANTUM INFORMATION GRADUATE PROGRAM AT THE UNIVERSITY OF WATERLOO IS PREPARING TOMORROW'S SCIENTIFIC LEADERS TO NAVIGATE THIS EXCITING NEW ENVIRONMENT.

Cross-disciplinary research and collaborations among leading computer scientists, engineers, chemists, mathematicians and physicists at IQC provide a learning environment like no other. Students in the Quantum Information Graduate Program experience the benefits of this setting, engaging in a study of quantum information science through a wide range of advanced courses and research projects. The scope of the program is comprehensive, with complementary perspectives across three faculties — Engineering, Mathematics and Science — providing the next generation of leaders in quantum information science and technology with training in a broad range of disciplines and methodologies.

Our students are well-positioned to move quantum information research forward. Through their studies and achievements, they will fuel the realization of real-world quantum technologies and scientific advancements that will benefit our society, reflecting the commitment of IQC and the University of Waterloo to scientific curiosity and a spirit of innovation.

John Watrous
Quantum Information Graduate Program Director

COURSES

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

FALL 2015

QIC 710
Quantum Information Processing

QIC 820
Theory of Quantum Information

QIC 880
Nanoelectronics for Quantum Information Processing

QIC 890
Solid State Photonic Devices

QIC 890
Modern Quantum Optics and Nanophotonics

WINTER 2016

QIC 750
Quantum Information Processing Devices

QIC 885
Quantum Electronics and Photonics

QIC 890
Applied Quantum Cryptography

QIC 890
Optical and Atomic Implementation

QIC 890
Relativistic Quantum Information

QIC 890
Entanglement and Nonlocality

SPRING 2016

PHYS 777
Sir Anthony Leggett Lecture Series: Topological Superconductors

QIC 890/891
Selected Advanced Topics in Quantum Information

QIC 890
Quantum Error Correction and Fault Tolerance

QIC 890
Introduction to Noise Processes

QIC 891
Topics in Quantum-Safe Cryptography

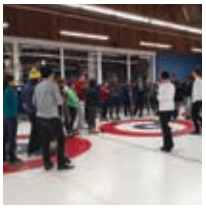
GRADUATE STUDENTS 2015-2016

Sascha Agne
Arash Ahmadi
Shahab Akmal
Rubayet Al Maruf
Thomas Alexander
Omar Alshehri
Matthew Amy
Vadiraj Ananthapadmanabha Rao
Elena Anisimova
Razieh Annabestani
Juan Miguel Arrazola
Golam Bappi
Marie Barnhill
Eduardo Barrera Ramirez
Jeremy Bejanin
Marian Berek
Kristine Boone
Matthew Brown
Brandon Buonacorsi
Arnaud Carignan-Dugas
Poompong Chaiwongkhot
Christopher Chamberland
Chung Wai Sandbo Chang
Jiahui Chen
Paulina Corona Ugalde
Alessandro Cosentino
Hillary Dawkins
Chunqing Deng
Rahul Deshpande
Olivia Di Matteo
John Donohue
Carolyn Earnest
Jennifer Fernick
Kent Fisher
Jeremy Flannery
Honghao Fu
Zhiwei Gao
Naimeh Ghafarian
Kaveh Gharavi
Nicolas Gonzalez
Matthew Graydon
Daniel Grimmer
Peter Groszkowski
Aimee Gunther
Holger Haas
Guiyang Han
Ian Hincks
Greg Holloway
Darryl Hoving
Anqi Huang
Vinay Iyer
David Jepson
Yuantao Ji
Tomas Jochym-O'Connor
Sarah Kaiser
Shitikanth Kashyap
Hemant Katiyar
Sumeet Khatri
Maria Kieferova
Feyruz Kitapli
Hyeran Kong
Anirudh Krishna
Meenu Kumari
David Layden
Han Le
Lin Li
Madelaine Liddy
Piers Lillystone
Jie Lin
Li Liu
Kevin Liu
Xudong Liu
Guofei Long
Xingliang (David) Lou
Benjamin Lovitz
David Luong
Xian Ma
Jean-Philippe MacLean
Christian Mastromattei
Michael Mazurek
Thomas McConkey
Corey Rae McRae
Evan Meyer-Scott
Maryam Mirkamali
Mohamad Niknam
Joachim Nsofini
Jean-Luc Orgiazzi
Martin Otto
Satish Pandey
Alex Parent
Kyungdoeck Park
Jihyun Park
Helen Percival
Clifford Plesha
Jitendra Prakash
Chris Pugh
Daniel Puzzuoli
Hammam Qassim
John Rinehart
Nayeli Azucena Rodriguez Briones
Romain Ruhlmann
Dolly Natalia Ruiz Amador
Vincent Russo
Allison Sachs
Shihan Sajeed
Jeff Salvail
Yuval Sanders
Dusan Sarenac
John Schanck
Behrooz Semnani
Ala Shayeghi
Feiruo Shen
Sumit Sijher
Nigar Sultana
Yongchao Tang
Alexander Valtchev
Guillaume Verdon-Akzam
Dhinakaran Vinayagamurthy
Sean Walker
Zimeng Wang
Chunhao Wang
Christopher Warren
Zak Webb
Kyle Willick
Christopher Wood
Yihang Yang
Joshua Young
Muhammet Yurtalan
Mohd Zeeshan

POSTDOCTORAL FELLOWS AS OF MARCH 31, 2016

Troy Borneman
Jean-Philippe Bourgoin
Aharon Brodutch
Franklin Cho
Patrick Coles
Joshua Combes
Jason Crann
Electra Eleftheriadou
Guanru Feng
Pol Forn-Diaz
Ying Dong
Vlad Gheorghiu
Sandra Gibson
Christopher Haapamaki
Christopher Herdman
Brendon Higgins
Jeongwan Jin
Milad Khoshnegar
Katanya Kuntz
Sangil Kwon
Chang Liu
Ying Liu
Dawei Lu
Filippo Miatto
Taisiya Mineeva
Ryo Namiki
George Nichols
Ibrahim Nsanzineza
Geovandro Pereira
Michele Piscitelli
Mahmood Sabooni
Fang Song
Rainer Stohr
Dave Touchette
Joel Wallman
Ben Yager
Huan Yang
Penghui Yao
Taehyun Yoon
Nengkun Yu
Hui Zhang
Yanbao Zhang

IQC GRADUATE STUDENT ASSOCIATION




The IQC Graduate Student Association (GSA) has always ensured that students maintain the right dose of play to go along with their work, and this year was no different. They started the summer off right by firing up the barbeques at the Research Advancement Centre (RAC) and partaking in some mid-June laser tag. The changing seasons ushered in the fourth annual bowling night, board and video games nights and the ultimate October activities — Halloween costume and door decorating contests. Westmount Golf and Country club helped stave off the winter blues with a curling lesson for the grad students, and Master's student **CHRISTOPHER WARREN** helped bring the thaw of spring with his hot chili that won the Spiciest Chili award at the second annual Chilli Cookoff in March, where **MATTHEW BROWN** and **KEVIN RESCH** both earned the Chili Champion title. The GSA is looking forward to bringing even more fun social activities to graduate students in the year to come.

GRADUATES

CONGRATULATIONS TO OUR 2015 GRADUATES!

Marie Barnhill
MMath Applied Mathematics (Quantum Information)

Jean-Philippe Bourgoin
PhD Physics

Chung Wai Sandbo Chang
MASc Electrical and Computer Engineering (Quantum Information)

Alessandro Cosentino
PhD Computer Science

Chunqing Deng
PhD Physics

Olivia Di Matteo
MSc Physics (Quantum Information)

Christopher Granade
PhD Physics (Quantum Information)

Peter Groszkowski
PhD Physics

Yuantao Ji
MASc Electrical and Computer Engineering

Martin Otto
MSc Physics

Kyungdeock Park
PhD Physics (Quantum Information)

Sadegh Raeisi
PhD Physics (Quantum Information)

Nayeli Azucena Rodriguez Briones
MSc Physics (Quantum Information)

Ala Shayeghi
MMath Combinatorics and Optimization (Quantum Information)

Alexander Valtchev
MMath Computer Science (Quantum Information)

Christopher Wood
PhD Physics (Quantum Information)

AWARDS AND RECOGNITION

FACULTY AWARDS AND GRANTS

MICHAL BAJCSY
- NSERC Discovery Grant (April 2015)

KYUNG SOO CHOI
- Early Researcher Award (April 2015)
- NSERC Discovery Grant (April 2014)
- NSERC Research Tools & Instruments (April 2014)

DAVID CORY
- Fellowship of the Royal Society of Canada (September 2015)
- Fellow, American Physical Society (October 2015)

THOMAS JENNEWEIN
- NSERC Discovery Grant (April 2015)
- American Physical Society Outreach Mini-Grant (May 2015)

RAYMOND LAFLAMME
- Waterloo-Technion Cooperation Program 2014 (May 2015)
- Canada Research Chair – Tier 1 (February 2016)
- NSERC Discovery Grant (April 2016)

DEBBIE LEUNG
- NSERC Discovery Grant (April 2016)

ADRIAN LUPASCU
- NSERC Research Tools & Instruments (April 2015)
- Waterloo-Technion Cooperation Program 2014 (May 2015)

MATTEO MARIANTONI
- NSERC General Research Fund (April 2015)

EDUARDO MARTIN-MARTINEZ
- NSERC Discovery Grant (April 2015)

VERN PAULSEN
- NSERC Discovery Grant (April 2016)

MICHAEL REIMER
- NSERC Discovery Grant (April 2016)

KEVIN RESCH
- FQXi Physics of What Happens (September 2015)
- NSERC Research Tools & Instruments (June 2016)

JOHN WATROUS
- 2014 Outstanding Performance Award (June 2015)

STUDENT AWARDS

EARNED BY IQC MASTER'S AND PhD STUDENTS IN THE 2015-16 FISCAL YEAR

Earned by IQC Master's and PhD students in the 2015-16 fiscal year

CAP-OSAF BORIS P. STOICHEFF MEMORIAL SCHOLARSHIP
Christopher Pugh

CANADA GRADUATE SCHOLARSHIP MASTER'S
Olivia Di Matteo
Jean-Philippe MacLean
Michael Mazurek
Sean Walker
Chunhao Wang

DAVID R. CHERITON GRADUATE SCHOLARSHIP
Dhinakaran Vinayagamurthy

IQC ENTRANCE AWARD
Eduardo Barrera Ramirez
Kristine Boone
Brandon Buonacorsi
Jennifer Fernick
Hyeran Kong
Benjamin Lovitz
Clifford Plesha
Nayeli Azucena Rodriguez Briones
Dhinakaran Vinayagamurthy

IQC ACHIEVEMENT AWARD
Hillary Dawkins

IQC DAVID JOHNSTON AWARD FOR SCIENTIFIC OUTREACH
Juan Miguel Arrazola
Carolyn Earnest
Sarah Kaiser

MIKE & OPHELIA LAZARIDIS FELLOWSHIP
Abel Molina
Sumit Sijher

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP — DOCTORAL
Matthew Amy
Olivia Di Matteo
Michael Mazurek
Sean Walker
Chunhao Wang

NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP — MASTER'S
Hillary Dawkins
Honghao Fu
Sumeet Khatri

NSERC POSTDOCTORAL FELLOWSHIP
Kent Fisher

MARIE CURIE GRADUATE STUDENT AWARD
Matthew Brown
Christian Mastromattei

NSERC VANIER CANADA GRADUATE SCHOLARSHIP
Jean-Philippe MacLean

ONTARIO GRADUATE SCHOLARSHIP
Kristine Boone
Hillary Dawkins
Kent Fisher
Sumeet Khatri
David Layden
Christian Mastromattei
Daniel Puzzuoli

OUTSTANDING ACHIEVEMENT IN GRADUATE STUDIES
Nayeli Azucena Rodriguez Briones

PRESIDENT'S GRADUATE SCHOLARSHIP
Matthew Amy
Kristine Boone
Hillary Dawkins
Kent Fisher
Sumeet Khatri
David Layden
Christian Mastromattei
Daniel Puzzuoli

QUEEN ELIZABETH II GRADUATE SCHOLARSHIP IN SCIENCE AND TECHNOLOGY
Matthew Brown

IQC ALUMNI

KALISTA (KELLY) ITAKURA

MASTER'S 2005, PhD 2010

During her time at IQC, former Master's of Mathematics student **KALISTA (KELLY) ITAKURA** focused on creating a quantum algorithm for testing the commutativity of matrices under supervisor **ASHWIN NAYAK**. She earned her PhD in Computer Science, focusing on Artificial Intelligence (AI) and Information Retrieval at the University of Waterloo.

Itakura acknowledges that her time at IQC helped her prepare for her current position as a risk manager at Scotiabank in Toronto, where she generates and oversees counterparty credit risk measures used by the trading desk. In the future, she hopes that quantum information science will allow for the creation of a practical quantum trading system so that she can start her own quantum AI trading company.

In the meantime, Itakura continues to pursue goals in her professional modelling and acting career, which includes making an appearance on the television comedy *The Big Bang Theory*. Itakura has previously acted on NBC's *Heroes Reborn* and was featured in a GO Transit marketing campaign. Her Erdős–Bacon number is seven.

AUDREY DOT

POSTDOCTORAL FELLOW 2014

During her time as a Postdoctoral Fellow at IQC, **AUDREY DOT** was using four-wave mixing in optical fibre to convert a single photon into a pair of photons. Dot, along with her supervisor **THOMAS JENNEWEIN**, PhD student **EVAN MEYER-SCOTT** and colleagues at McGill University, Montreal, sent a single photon through the optical fibre with a strong pump beam to produce a pair of photons with increased efficiency compared to previous methods. Dot then brought her knowledge and research skills to the smart thermostat company Qivivo, where she worked on machine learning algorithms as a Physicist Engineer.

Now she is at the Alternative Energies and Atomic Energy Commission (CEA) in France, an industrial research centre. She is working on 3D time-resolved diffused optical tomographic reconstruction for medical applications, a process used to model organs like the heart in order to find problems such as tumours and occlusions quickly and without intrusion.

GUS GUTOSKI

MASTER'S 2006, PhD 2009, POSTDOCTORAL FELLOW 2016

GUS GUTOSKI is using the skills he gained at IQC to develop quantum-safe security for conventional computing systems at ISARA, a Waterloo-based company founded in 2015. While earning his Master's and PhD degrees at IQC, Gutoski studied quantum computational complexity theory and the mathematical foundations of quantum information. During his time as a postdoctoral fellow, he gradually shifted focus to quantum cryptography.

"At IQC, I acquired a level of academic maturity that made it easy to identify and transfer the relevant skills and knowledge I already possessed and to identify and acquire the new skills and knowledge necessary for quantum-resistant cryptography," he said. This foundation eased his transition to ISARA where he evaluates and improves cryptographic algorithms. He is excited to investigate his ideas about improving lattice-based signature schemes in the near future.

A STREAM OF IDEAS

IT ALL BEGINS WITH AN IDEA.

The world of research is the domain of ideas, where theories are developed, flowing downstream for experimental testing and refinement. Often, fundamental research flows back upstream into the domain of ideas, to enhance and deepen our understanding of how the universe works. Other ideas keep flowing downstream, moving through proof of concept, prototyping and then eventually to the domain of services, products and tangible goods where value accumulates.

"It takes about seven to eight years for an emerging technology to evolve into something that is commercially tangible," noted **MARK PECEN**, CEO of Approach Affinity Inc. and Entrepreneur-in-Residence at IQC. "Value increases downstream, so our objective is to move the outputs of an institute such as IQC to a broader community where value creation downstream is more likely."

At IQC, Pecen helps aspiring entrepreneurs move their ideas downstream. Building strong connections between research and industry also facilitates the downstream flow of technologies to the market. Technologies based on research at IQC are already flowing.

One example is ISARA Corporation, a startup founded in 2015 by **SCOTT TOTZKE** and **MIKE BROWN**. ISARA is designing commercial cryptographic solutions to protect computers and networks against attacks by quantum computers capable of comprising public-key cryptography.

IQC alumni, **GUS GUTOSKI** and **KASSEM KALACH**, are two of 19 full-time employees working towards ISARA's mission to raise awareness of and build solutions to protect systems against quantum threats. "There is an industry need to turn this research into marketable applications. ISARA was created as a landing zone for quantum-safe cryptography research and researchers emerging from IQC," said Pecen, who is also on board as ISARA's Chief Operating Officer.

IQC and Canada are positioned to lead the quantum cryptography industry. "We have the right ingredients here and need to apply the right recipes through standardization," said Pecen. "The ideas are here. Investing in people is the right way to grow an organization like this. IQC is one of the places of the future for Canada."

SCIENTIFIC OUTREACH

RECOGNIZING COMMUNITY OUTREACH AND ENGAGEMENT

CONGRATULATIONS TO **JUAN MIGUEL ARRAZOLA** AND **CAROLYN EARNEST**, RECIPIENTS OF THE 2015 IQC DAVID JOHNSTON AWARD FOR SCIENTIFIC OUTREACH. THIS AWARD WAS CREATED IN HONOUR OF HIS EXCELLENCY DAVID JOHNSTON, GOVERNOR GENERAL OF CANADA, FOR HIS PASSION, LEADERSHIP AND ENTHUSIASM FOR CONTINUOUS LEARNING, INNOVATION AND ACHIEVEMENT. JOHNSTON WAS PRESIDENT OF THE UNIVERSITY OF WATERLOO FROM 1999 TO 2010. THE AWARD RECOGNIZES STUDENTS WHO HAVE SHOWN AN OUTSTANDING COMMITMENT TO SCIENTIFIC OUTREACH AND COMMUNITY ENGAGEMENT.

JUAN MIGUEL ARRAZOLA

Former PhD student **JUAN MIGUEL ARRAZOLA** does scientific outreach because he enjoys it — a lot. "I also think that it is a waste when scientific knowledge is retained by specialists when it only takes a bit of effort to share this richness with the rest of the world," he said. Arrazola has done his best to share knowledge by launching the IQC blog *Our quantum world*. Among his contributions to the blog is the three-part series "Anyone can understand quantum mechanics", where he teaches the basics of the theory in a way that anyone can understand.

"Outreach efforts are beneficial to their immediate community, but with a blog, we can spread our ideas to anyone with an Internet connection," he said. He is currently a postdoctoral fellow at the National University of Singapore, where his research is in the field of quantum communication.

CAROLYN EARNEST

PhD student **CAROLYN EARNEST** envisions a future where science is more inclusive of women, First Nations and other minority groups. "I think that science is ultimately tied up with the cultural background of the ones doing it, and when you start to introduce more kinds of people, then you have a diversity of ideas that get explored, and that's good for everybody," she said.

She is doing her part to realize that vision as the founding president of the University of Waterloo Women in Science group and as a member of the board of FemPhys and IQC's Equity and Inclusivity Committee. She also leads by example by working to make quantum computing with nanocircuits more scalable with components like scalable wiring and gates in the Laboratory for Digital Quantum Matter.

SHARING, EDUCATING, INSPIRING, CONNECTING.

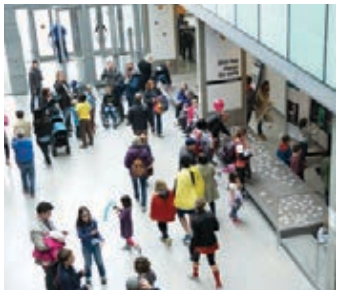
IQC BRINGS THE WORLD OF QUANTUM INFORMATION SCIENCE AND TECHNOLOGY TO THE CURIOUS-MINDED THROUGH UNIQUE OUTREACH OPPORTUNITIES DESIGNED TO SHARE THE FASCINATING RESEARCH THAT IS CHANGING THE WAY WE LIVE, WORK AND PLAY.

QUANTUM: MUSIC AT THE FRONTIER OF SCIENCE

The quantum symphony *Quantum: Music at the Frontier of Science* was presented as part of the Ontario Scene at the National Arts Centre in Ottawa on May 3. A collaboration between the Kitchener-Waterloo Symphony and IQC, this musical journey explores the parallels between music and science.

DISCOVERING QUANTUM INFORMATION SCIENCE AND TECHNOLOGY

IQC hosted an open house on Saturday, October 3 as part of Waterloo's Reunion weekend festivities. More than 700 Waterloo alumni and community members learned about quantum information research from students and faculty members and explored hands-on science activities hosted by Waterloo's Let's Talk Science and Engineering Science Quest groups. Other highlights included a Q-Kids Science Show, a fireside chat with executive director **RAYMOND LAFLAMME**, guided by radio host **MIKE FARWELL** on embracing the quantum revolution, and the début of *Quantum Cats*, the quantum-inspired version of the game *Angry Birds*™.



CELEBRATING LIGHT

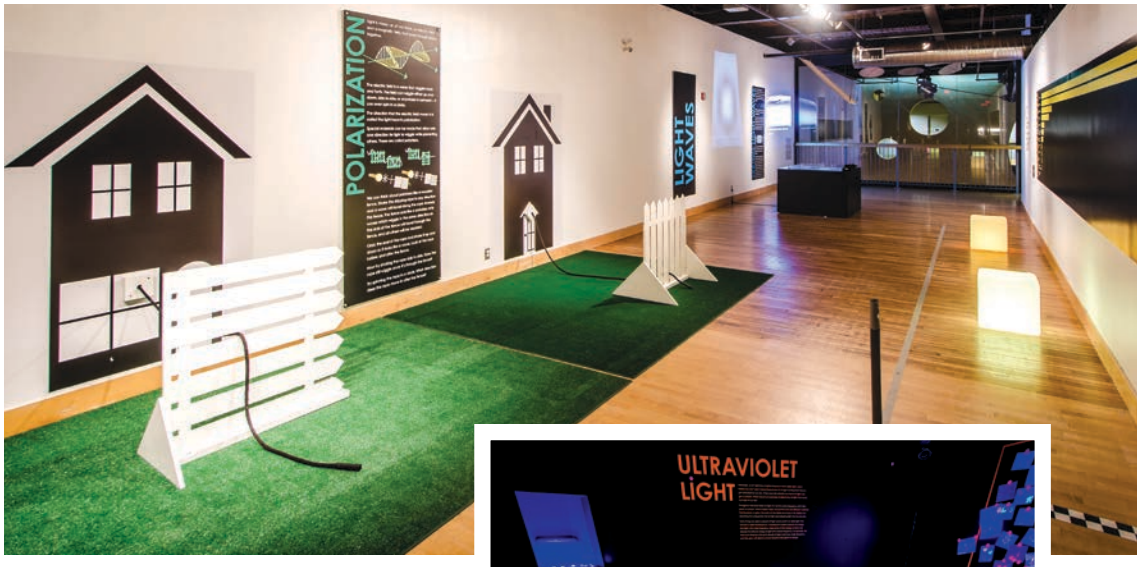
MOST OF OUR MODERN TECHNOLOGY — NOT TO MENTION LIFE AS WE KNOW IT — COULD NOT EXIST WITHOUT LIGHT. IN RECOGNITION OF ITS IMPORTANCE, THE UNITED NATIONS (UN) GENERAL ASSEMBLY NAMED 2015 AS THE INTERNATIONAL YEAR OF LIGHT AND LIGHT-BASED TECHNOLOGIES (IYL 2015). A GROUP OF GRADUATE STUDENTS FROM THE UNIVERSITY OF WATERLOO STUDENT CHAPTER OF THE OPTICAL SOCIETY (OSA) BROUGHT LIGHT TO LIFE IN *LIGHT ILLUMINATED*, AN EXHIBITION FEATURED AT THEMUSEUM IN DOWNTOWN KITCHENER FROM OCTOBER 2015 TO MARCH 2016. IQC PhD STUDENTS **AIMEE GUNTHER**, **MIKE MAZUREK**, **KENT FISHER**, **JEAN-PHILIPPE MacLEAN** AND **SARAH KAISER** ALONG WITH MASTER'S STUDENT **IAN ANDREWS** FROM THE DEPARTMENT OF PHYSICS AND ASTRONOMY CREATED AND CURATED THE EXHIBITION, WHICH DREW OVER 40,000 VISITORS.

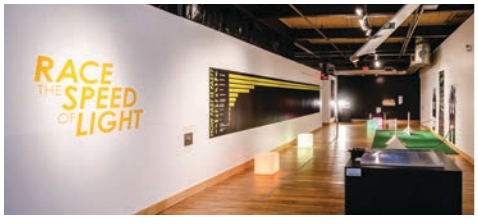
"The museum exhibit is a gateway for people who are stumbling at the barrier of perceived difficulty in the science, technology, engineering and mathematics (STEM) fields. By being hands-on with exhibit activities, they learned without the stress of knowing there is a test at the end."

– AIMEE GUNTHER

"*LIGHT Illuminated* allowed local members of our community to showcase the variety of ways that they use light to create modern technology and art. Visitors got to choose words to display in a beautiful piece of art, see what they look like in infrared, and watch a dragon's scales shimmer and shift colours. These components of the exhibit, among many others, were provided by individuals and businesses from the Waterloo Region."

– MICHAEL MAZUREK





"The exhibit helped normalize science as something real people do. We sought to teach concepts about light in tangible, fun, and perhaps new ways. Also, in the Region of Waterloo we are fortunate to have a wellspring of scientific research and technological development, as well as an engaged community eager to learn about what is going on in the scientific world. It was our goal to tell visitors of THEMUSEUM about some of the amazing things done with light right here in our city."

– KENT FISHER

"With *LIGHT Illuminated*, we wanted to engage and inform the community about light and also the role that local companies have in developing these technologies. The goal was to get a younger audience excited about light and the fun things that we can do with it; and for the general audience, to inform them about how light-based companies in Waterloo are contributing to products and tools that we use on a daily basis, such as fibre optics used for the internet, polarization in sunglasses, refraction in glasses, thermal cameras and more."

– JEAN-PHILIPPE MacLEAN

"*LIGHT Illuminated* gave the community the opportunity to appreciate light and how fortunate we are to utilize it in so many areas in our lives. For example, the exhibit's fire inspector ran the light racetrack and figured out that in the time it took him to run the track, light had gone to the moon and back several times! His eyes lit up and he was surprised at the speed of light. That moment he gained an understanding of the speed of light from our exhibit was an incredible experience for me."

– IAN ANDREWS

THANK YOU

to the community partners who contributed to the success of *LIGHT Illuminated*:

THEMUSEUM
The Optical Society
The American Physical Society
Christie Digital
COM DEV
FiberTech Optica
Teledyne DALSA
The University of Waterloo
Wizard Labs
Department of Knowledge Integration, University of Waterloo

CONFERENCE, WORKSHOP AND SEMINAR HIGHLIGHTS

Canada Excellence Research Chairs
Chaires d'excellence en recherche du Canada

CANADA EXCELLENCE RESEARCH CHAIRS (CERC) ANNUAL MEETING

Waterloo researchers **DAVID CORY**, CERC in Quantum Information Processing, and **PHILIPPE VAN CAPPELLEN**, CERC in Ecohydrology, chaired the fifth annual CERC meeting hosted at the University of Waterloo April 13-14.

NANOSCALE MAGNETIC RESONANCE IMAGING (NANOMRI) CONFERENCE

The fifth NanoMRI conference brought together an interdisciplinary community of scientists and engineers at IQC July 27-31. The conference focused on emerging technologies for detecting spins on the nanometer scale, and the application of these technologies to biology, condensed matter systems and quantum information.

QUANTUM INNOVATORS

Exploring the frontiers of quantum physics and engineering was the focus of the fourth Quantum Innovators conference hosted by IQC. Fifteen of the most promising young researchers in this field came together from October 4-7 to share their work and make connections. Among the participants was **WEI TSEN**, now Assistant Professor at IQC and the Department of Chemistry.

SC

Schrödinger's Class

IQC welcomed 20 high school science educators for the very first workshop for teachers December 5-6. Through lectures and hands-on activities, teachers gained a deeper understanding of quantum mechanics, with a focus on how to bring quantum information science and technology back to their classrooms to share with their students. Senior Manager, Scientific Outreach **MARTIN LAFOREST** guided the teachers through scientific concepts including wave-particle duality, superposition, quantum computing algorithms, entanglement and quantum cryptography.

USEQIP

Undergraduate School
on **Experimental Quantum**
Information Processing

THE TWO-WEEK PROGRAM, USEQIP, COMBINES BOTH A THEORETICAL AND EXPERIMENTAL APPROACH TO STUDYING QUANTUM INFORMATION AND IS AIMED AT 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.

KRISTINE BOONE

USEQIP 2014

While working on her BSc majoring in astrophysics at the University of Calgary, **KRISTINE BOONE** applied to USEQIP. Her experience at USEQIP solidified her decision to pursue graduate studies focusing on quantum information science.

"I applied to USEQIP to find out what the field of quantum information is like. The professors teaching the classes were really excited to share this topic," Boone said, reflecting on her time at USEQIP in 2014. "I learned so much about the field and about what it's like to do research at IQC."

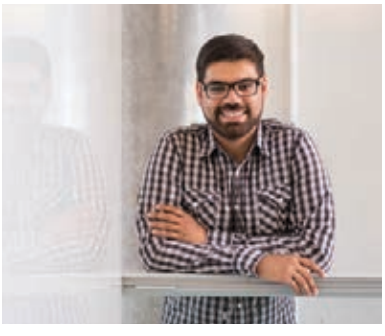
Her newfound knowledge helped her finish her undergraduate honours thesis project and contributed to research she did following graduation with former supervisor **CHRISTOPH SIMON**. In collaboration with others, they discovered that axons in the brain are waveguides for photons, suggesting that there may be a link between quantum information and consciousness.

Upon finishing her undergraduate studies, Boone knew that she wanted to return to IQC. Now a Master's student at IQC, Boone is currently investigating assumptions underlying randomized benchmarking, which may be useful for characterizing errors in a quantum system. "Attending USEQIP definitely contributed to where I am in my academic career," said Boone.

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. LAUNCHED IN 2008, THERE ARE 275 QCSYS ALUMNI FROM 20 COUNTRIES ACROSS THE GLOBE.



ANDREW ANDRADE

QCSYS 2010

Transmitting messages with coins and boxes, decrypting laser-sent messages — these are the memories that QCSYS alumnus **ANDREW ANDRADE** remembers most fondly. "My QCSYS experience helped me realize I was more interested in hands-on applications of science and technology," he said. This interest has manifested in Andrade's work; he invented a self-driving bicycle platform, wrote an award-winning research paper on the application of artificial intelligence and predictive analytics in the oil and gas industry, and co-founded a business called PetroPredict that uses data analytics for early life detection of integrity issues in oil fields.

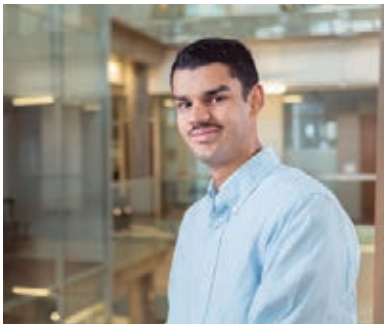
Andrade agrees QCSYS has helped him get to this point. "The biggest thing I gained from QCSYS is the synergistic approach to emerging fields and technologies." After earning his Mechatronics Engineering degree at Waterloo, he plans to continue with this approach at Palantir Technologies as a deployment strategist.

MAYA BURHANPURKAR

QCSYS 2014

MAYA BURHANPURKAR is a 17-year-old student, scientist, entrepreneur and volunteer who was honoured with Canada's Top 20 Under 20 Award. In 2014, she attended QCSYS, which she credits with helping to solidify her interest in physics, engineering and computing. "Students often don't have experience in the field they're choosing to study in university. QCSYS definitely gave me experience in the field, which was great," she said. It also gave her the opportunity to meet like-minded people from around the world, some of whom she still keeps in contact with. She advises future students "to make an effort to get to know others because they have really cool backgrounds — that's why they're at QCSYS."

Burhanpurkar is taking a gap year, before attending Harvard, to work on the development of an autonomous wheelchair for quadriplegics at the University of Toronto's renowned Institute for Aerospace Studies.



TWESH UPADHYAYA

QCSYS 2014

For QCSYS alumnus **TWESH UPADHYAYA**, he couldn't resist the allure of IQC's research environment. Under the guidance of IQC researcher **MICHAL BAJCSY**, his grade 12 science fair project consisted of designing a polarization-selective photonic crystal membrane in silicon nitride, with application as the reflective surface of an all-optical, single-photon transistor. He won the gold medal and best in category at the regional competition and a silver medal and the Canadian Association of Physicists (CAP) Physics Prize at the Canada-Wide Science Fair. He returned this summer to work on a framework for universal quantum circuit synthesis as an Undergraduate Research Assistant (URA) with researcher **MICHELE MOSCA**.

Currently earning a degree in Engineering Science at the University of Toronto, Upadhyaya credits QCSYS with stoking his passion for physics by revealing both the potential of quantum mechanics and the dense mysteries that remain to be solved within it. He offers this advice to future QCSYS students: "you have access to top researchers, so make sure you ask questions and do as much as you can."

JOHN FISH

QCSYS 2015

QCSYS gave **JOHN FISH** the knowledge he needed to make a video explaining the Einstein-Podolsky-Rosen (EPR) Paradox that made him a finalist in the Breakthrough Junior Challenge. Since then, he has served as a counselor at Engineering Science Quest (ESQ) at the University of Waterloo and is currently working on a software platform that will allow teachers to easily create and deliver computer programming curriculum to students via the internet so students can interact with it on accessible devices.

Unsurprisingly, Fish says that he is more interested in the computing side of quantum science. "What I think is cool about this is that very difficult problems could soon become trivial by using this really weird physics," he said. He appreciates his experience at QCSYS because of his discussions with researchers that helped him decide his career path and because of the intensity of the program.

ENCOURAGING YOUTH TO EXPLORE QUANTUM INFORMATION SCIENCE

IQC continues to educate and excite students about quantum information science and technology (QIST) through hands-on workshops, lectures and lab tours. This year:

41,950+ students and community members introduced to QIST

1,200+ youth participated in a hands-on workshop, lab tour or lecture

138 high school teachers received the tools to share quantum information with students in their classroom

31 outreach activities focused on quantum information science

IQC BY THE NUMBERS

APRIL 1, 2015 TO MARCH 31, 2016

IQC IS HOME TO...

24 faculty members

4 research assistant professors

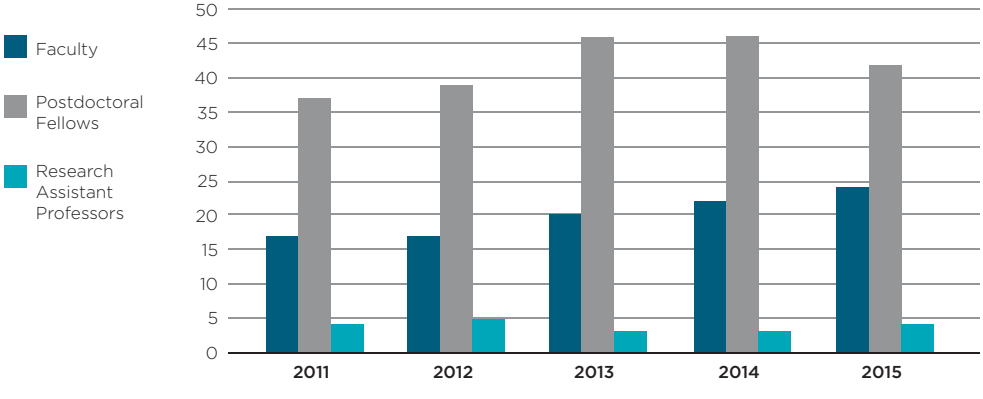
41 postdoctoral fellows

30 long-term visitors

116 graduate students

7 technical specialists

FACULTY & POSTDOCTORAL FELLOWS



PUBLICATIONS

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

IQC RESEARCH PUBLISHED IN PROMINENT JOURNALS SINCE 2010

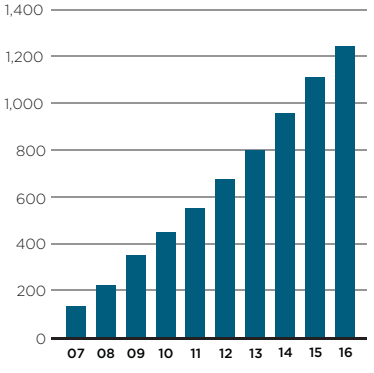
PUBLICATION	10-11	11-12	12-13	13-14	14-15	15-16
Nature	1	1	1		2	1
Nature Photonics	1	1		3	2	1
Nature Physics	5	3	2	3		2
Nature Communications		1	1	1	5	3
Physical Review Letters	14	17	14	14	16	17
Science	1	2	1	1	3	
STOC	2					
FOCS		1	1			
Journal of Mathematical Physics	2	4	6	4	4	6

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

CUMULATIVE PUBLICATIONS BY IQC RESEARCHERS

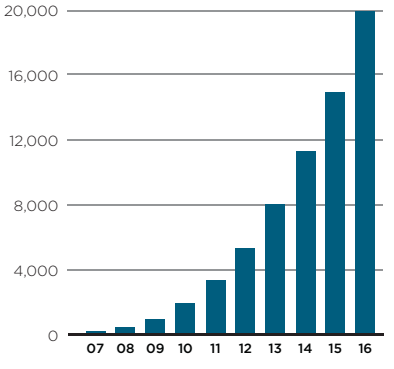
132 publications by IQC researchers in fiscal 2016

1,242 publications by IQC researchers since 2002



CUMULATIVE CITATIONS OF IQC PUBLICATIONS

19,993 cumulative citations for all IQC publications since 2002



**Source for Publications and Citations: Thomson Reuters' Web of Science on April 1, 2016. Data compiled using an address search for Institute for Quantum Computing (inst* quantum comp*). Citations are cumulative for all IQC publications for all years.*

ENABLING QUANTUM RESEARCH

EFFECTIVE TOOLS ENHANCE PRODUCTIVITY. STEVE WEISS, IQC'S ASSOCIATE DIRECTOR, INFORMATION TECHNOLOGY (IT), APPRECIATES THE APPLICATION OF ELEGANT TOOLS THAT INCREASE EFFICIENCIES. THROUGHOUT HIS CAREER, WEISS HAS STRATEGICALLY APPLIED TECHNOLOGY TO ENHANCE PRODUCTIVITY FOR BOTH LARGE AND SMALL CORPORATIONS.

Weiss leads the IT team at IQC. The team's primary role is to facilitate the realization of technologies and tools that enable researchers to focus on their work. "We free researchers from having to deploy and support classical computing technology outside of the lab," Weiss said. This includes sourcing technology resources that already exist on campus or developing tailored solutions. Needs vary from implementing custom software systems, to outfitting collaboration spaces with technology, to preparing workstations for daily use.

If there is a gap between technological needs and what is available, Weiss and his team support researchers' goals by investing in design-based outcomes to meet those needs. One example is the new computational lab now up and running in the Mike and Ophelia Lazaridis Quantum-Nano Centre. Weiss saw that graduate students did not have on-demand access to high-end computing equipment needed to run complex computational simulations. Weiss' team set to work on the installation of a pop-up computational lab to fill that need. Now students can use the proper equipment to achieve faster turnaround times when running simulations.

Weiss and his team also work closely with the Quantum NanoFab group at IQC. To enhance daily operational processes for the cleanroom and fabrication facility, the IT team has implemented an environmental monitoring and video system and developed custom order and inventory tracking. "The Quantum NanoFab continues to benefit tremendously from IT's expertise and exceptional approach to customer service," said **VITO LOGIUDICE**, Director of Operations for the Quantum NanoFab.

The IT group is evolutionary; Weiss notes that the job is never complete as technology evolves and user needs change. "We listen and try to predict emerging technology needs," said Weiss. "It's not always easy to see what's around the bend." This challenge is best met through embracing technology transformation and working closely with researchers at the institute, according to Weiss.

Looking at the bigger picture, Weiss sees his team contributing fundamentally to a high-quality research environment at IQC. Providing classical computing tools allows faculty members and students to focus on their quantum research goals.

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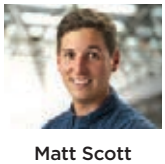

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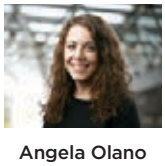

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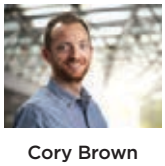

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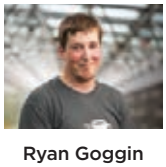

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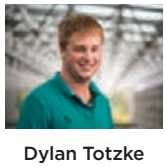

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ADVANCING SCIENTIFIC DISCOVERY

MESSAGE FROM THE PRESIDENT OF THE UNIVERSITY OF WATERLOO

THE UNIVERSITY OF WATERLOO IS COMMITTED TO ADVANCING THE STATE OF SCIENCE IN CANADA, WHILE LEVERAGING OUR DEEP CONNECTION TO INDUSTRY TO MOBILIZE RESEARCH FOR FULL SOCIAL AND ECONOMIC IMPACT.

It's what we were uniquely founded to do 60 years ago next year. It remains today and always our mission. And the Institute for Quantum Computing is a powerful example of that mission in action.

We believe IQC at the University of Waterloo is a leading example of how a modern, progressive university can take the lead for Canada in strategic frontier disciplines and industries.

Working together with some of the world's best scholars, phenomenal partners such as Mike and Ophelia Lazaridis, and inspired by our opportunity to fundamentally change technology as we know it by securing quantum breakthroughs, Canada's Quantum Valley is leading the world through the second quantum revolution.

This is the right discipline, at the right university, in the right community, at the right time. The University of Waterloo's historic strengths in talent development through co-operative education, our research depth in quantum science, and the maturing constellation of supportive research centres and partners in our community, show that the Waterloo region — Canada's Quantum Valley — has deliberately established a powerful ecosystem to enable breakthroughs and mobilization. Nowhere else on Earth have conditions like these been set so carefully, intentionally, and successfully.

That is thanks to countless partners and supporters, working in unison to create something truly special. On that note, and as IQC begins its 15th year, I would like to acknowledge Mike and Ophelia Lazaridis for their generous support and remarkable vision; Raymond Laflamme for his tremendous leadership of the Institute; and researchers across the faculties of Science, Mathematics, and Engineering for their groundbreaking contributions to quantum technology.

Most importantly, thank you to all IQC students, whose fascination and experience with quantum science is changing the world around us.

Feridun Hamdullahpur
President and Vice-Chancellor
University of Waterloo

THANK YOU

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

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

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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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