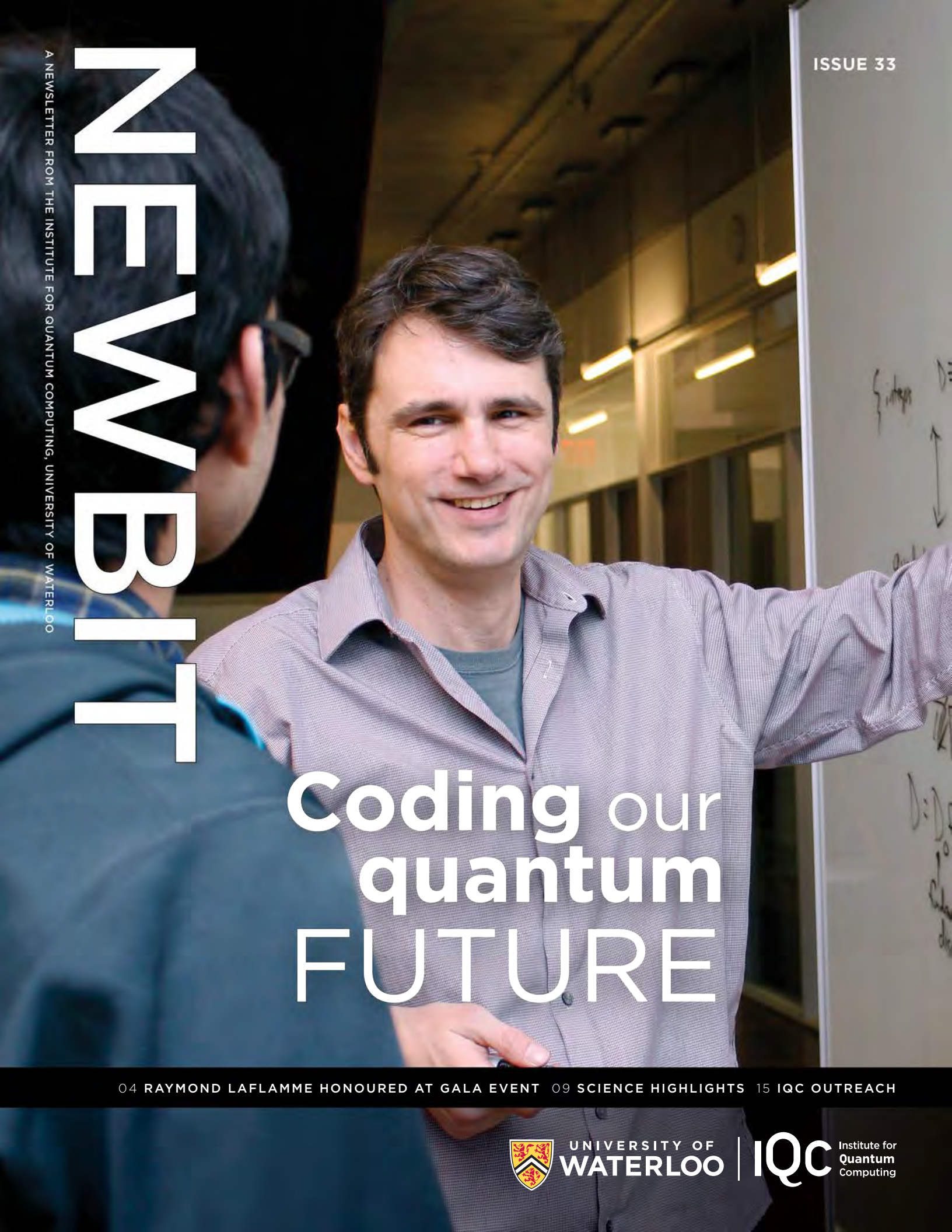


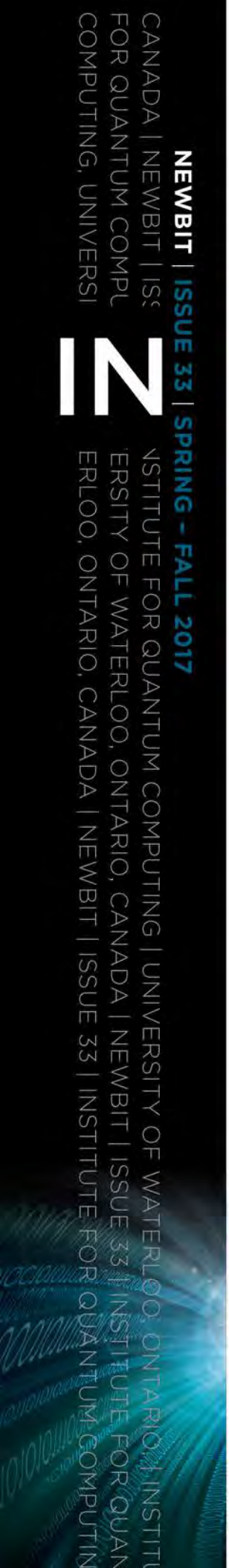
NEWSBIT

A NEWSLETTER FROM THE INSTITUTE FOR QUANTUM COMPUTING, UNIVERSITY OF WATERLOO

ISSUE 33

Coding our quantum FUTURE

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing



UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

this issue

ON THE COVER

Faculty member JON YARD works on a problem with undergraduate research assistant SANKETH MENDA

Cover Photo by: IQC

ISSUE 33

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FROM THE EDITOR

Anniversaries are both a time to look back at accomplishments and look towards future possibilities. Celebrating IQC's 15 years of discovery and innovation was no exception. Over the last year, we honoured the extraordinary vision and leadership of **RAYMOND LAFLAMME** (pg 4), paid tribute to the seminal work of **ALEXEI KITAEV** (pg 13) and celebrated a successful cross-country tour of *QUANTUM: The Exhibition* (pg 22).

But we also pushed boundaries, set new goals and expanded our reach. For the first time, IQC offered two different Quantum Innovators workshops to bring together the most promising young postdoctoral fellows and early career researchers (pg 14). *QUANTUM: The Pop-Up Exhibition* pushed geographical boundaries on a four-country tour across Europe, while at home, we welcomed researchers from across Canada to the Women in Physics Conference (pg 12).

Looking ahead to what the next 15 years might hold is difficult because we are continually called to re-envision what we think is possible. **THOMAS JENNEWEIN** and the Quantum Encryption and Science Satellite (QEYSSat) team proved the viability of quantum satellite communications. **JON YARD**, our feature profile in this issue (pg 6), is merging small-scale fault tolerance systems with the greater whole, bringing us one step closer to developing new quantum algorithms. We also welcomed two new Faculty members— **CHRISTINE MUSCHIK** and **WILLIAM SLOFSTRA**— whose research portfolios promise to accelerate discoveries and drive collaborations.

IQC has achieved so much in less than two decades. The next 15 years are ours to define.

CHRISTINE BEZRUKI,

Senior Manager, Communications, Institute for Quantum Computing

New **FACULTY** MEMBERS

William Slofstra

While investigating non-local games in 2016 as a research assistant professor at the Institute for Quantum Computing (IQC), **WILLIAM SLOFSTRA** discovered a solution to the Tsirelson problem – a longstanding question in mathematics. His answer gets at the nature of how entanglement is modeled, helping mathematicians understand the ways in which two spatially separated systems behave.

In July 2017, Slofstra was named an assistant professor at IQC and the Department of Pure Mathematics. He continues to tackle further problems in non-local games, Lie theory, representation theory, algebraic combinatorics and the geometry of entanglement.

Christine Muschik

From the Institute of Theoretical Physics at the University of Innsbruck, theorist **CHRISTINE MUSCHIK** joined IQC as an assistant professor in the Department of Physics and Astronomy in November 2017.

As leader of the Quantum Optics Theory group, Muschik explores quantum simulation to model the interactions of fundamental particles on a level of complexity too great to be achieved on a classical computer. She also aims to use novel dissipative techniques in quantum error-correction to design a sustainable quantum network with applications in quantum communications, sensing, cloud computing and fundamental tests of nature. ■

CELEBRATING 15 years OF DISCOVERY & INNOVATION

IQC was established in 2002 with a vision: to create a world-class centre in quantum information science at the University of Waterloo. Fifteen years later, that vision is reality, due in no small part to the leadership of IQC's founding executive director **RAYMOND LAFLAMME.**

Outgoing Executive Director **RAYMOND LAFLAMME** is honoured for his leadership and contributions to IQC during June's gala event celebrating 15 years of discovery and innovation.

On June 22, 2017, dignitaries, special guests and fellow scientists from around the world came together to celebrate both IQC's anniversary and the contributions of Raymond Laflamme, who ended his term as executive director on June 30, 2017.

The evening was hallmarked by a video from Canada's Prime Minister and self-proclaimed "quantum geek," **JUSTIN TRUDEAU**, who celebrated the Canadian researchers leading the quantum revolution: "What you do here truly has the potential to transform the world, and I, as Prime Minister and a quantum geek, couldn't be prouder."

His Excellency **DAVID JOHNSTON**, then Governor General of Canada, also praised the work of IQC and Laflamme, whom he helped to recruit from Los Alamos National Laboratory. "Ray...we salute you for all you have done in leading our scientific community," said Johnston via video, "but also our general community in such remarkable ways."

MIKE LAZARIDIS, whose vision set quantum research at Waterloo in motion, reflected on IQC's history, its future and the immense opportunities quantum technologies hold for Canada. He joined University of Waterloo President and Vice-Chancellor, **FERIDUN HAMDULLAHPUR** in commending Laflamme on his leadership and ability to bring a whole community together to achieve a common goal.

Other dignitaries and research colleagues who sent in video remarks to celebrate IQC's anniversary included Ontario Premier, **KATHLEEN WYNNE**; Director of the Perimeter Institute **NEIL TUROK**; and **JUAN PABLO PAZ**, long-time friend of Laflamme and head of the Quantum Foundations and Information group in Buenos Aires.

WEB **bit.ly/IQC-turns-15** ■

(Above, left) **RAYMOND LAFLAMME** is warmly welcomed to the stage by **MIKE LAZARIDIS**

(Above) **RAYMOND LAFLAMME** reflects on his time at IQC during his keynote address

FERIDUN HAMDULLAHPUR and **MIKE LAZARIDIS** commend **RAYMOND LAFLAMME**'s leadership

FEATURE ARTICLE

Coding our quantum FUTURE

The math that drives quantum computing

Take one look into JON YARD's office, and you wouldn't be surprised to learn he's a quantum theorist. A whiteboard filled from top to bottom with complex algebra sits on the wall opposite his desk. In the corners are layers of frantic smudges from equations erased, scribbled over and erased again.

Yard studies quantum information science. He uses ideas from physics, mathematics and computer programming to investigate the theory behind quantum systems and networks.

While other researchers work to build the physical parts of a quantum processor, Yard is looking at the problem from the top down. His goal is to figure out the capabilities and limitations of those systems for processing information.

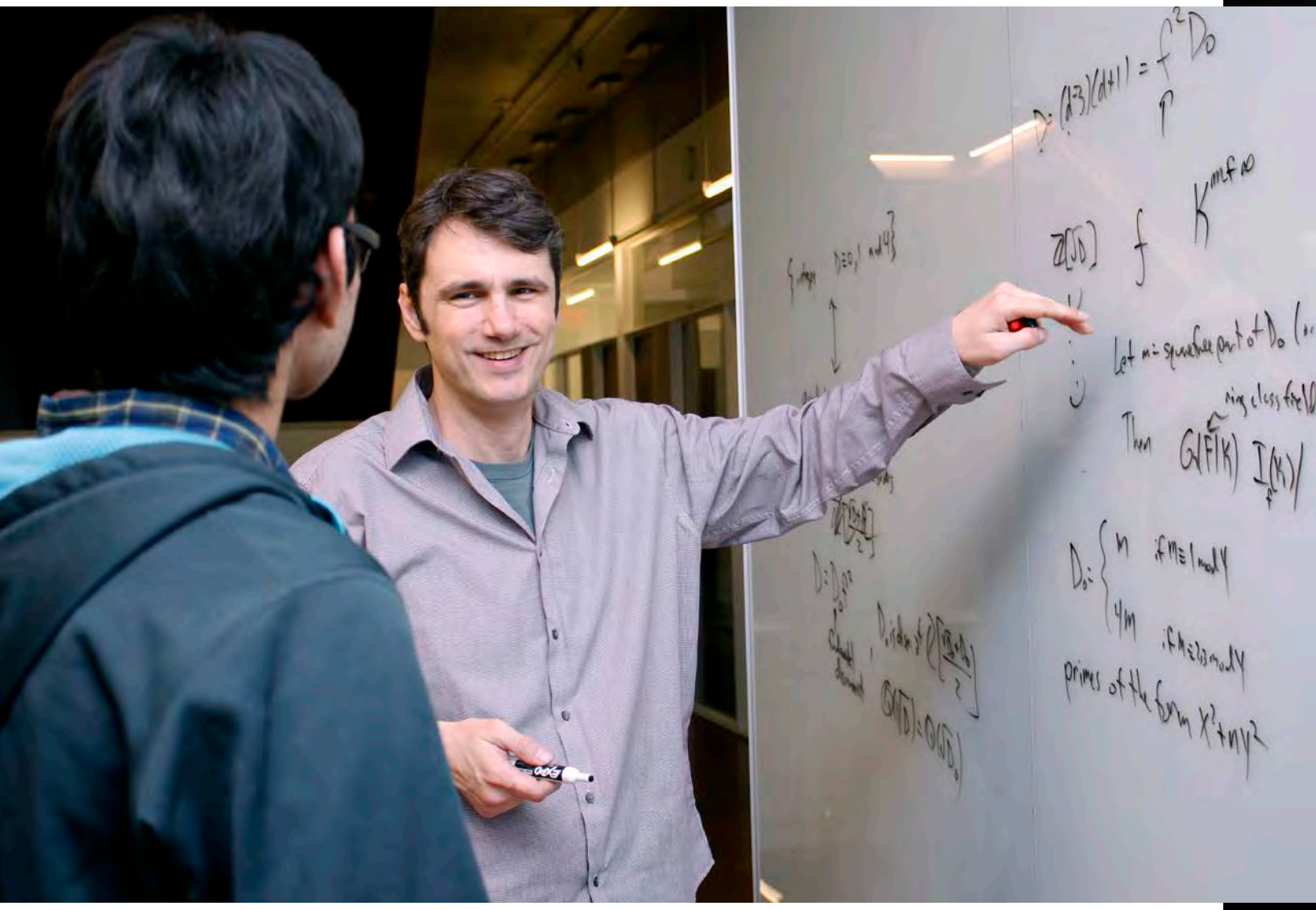
THE NUTS AND BOLTS OF COMPUTATION

From a high level, quantum processors aren't so different from the ones we use today.

In classical computing, the basic information unit is a bit. These bits are operated on by logic gates, and a series of these gates makes up a typical circuit. If programmers want to employ this system to solve complex problems, they write step-by-step instructions called algorithms that tell the computer exactly what they want it to do.

One model for quantum computation works in much the same way. It uses quantum circuits composed of a series of quantum gates to manipulate individual qubits. Quantum algorithms then execute instructions that exploit the quantum mechanical properties of superposition and entanglement to solve problems that could be much more difficult for, or take longer on, a classical computer.

IQC researcher JON YARD is a professor in the Department of Combinatorics & Optimization in the Faculty of Mathematics, and an Associate Faculty at the Perimeter Institute for Theoretical Physics.



Theoretical research is often a collaborative effort. Here, JON YARD works on a problem with undergraduate research assistant SANKETH MENDA.

Determining which problems admit a quantum speedup is an important challenge.

As Yard says, "We need new quantum algorithms." Additionally, certain quantum gates appear to require enormous resources each time they are used. Minimizing the use of these gates allows longer and more reliable computations to be carried out at tremendous savings in cost. Codes for reliably implementing gates also need to be optimized, drawing on our current understanding of how quantum computers might work in practice.

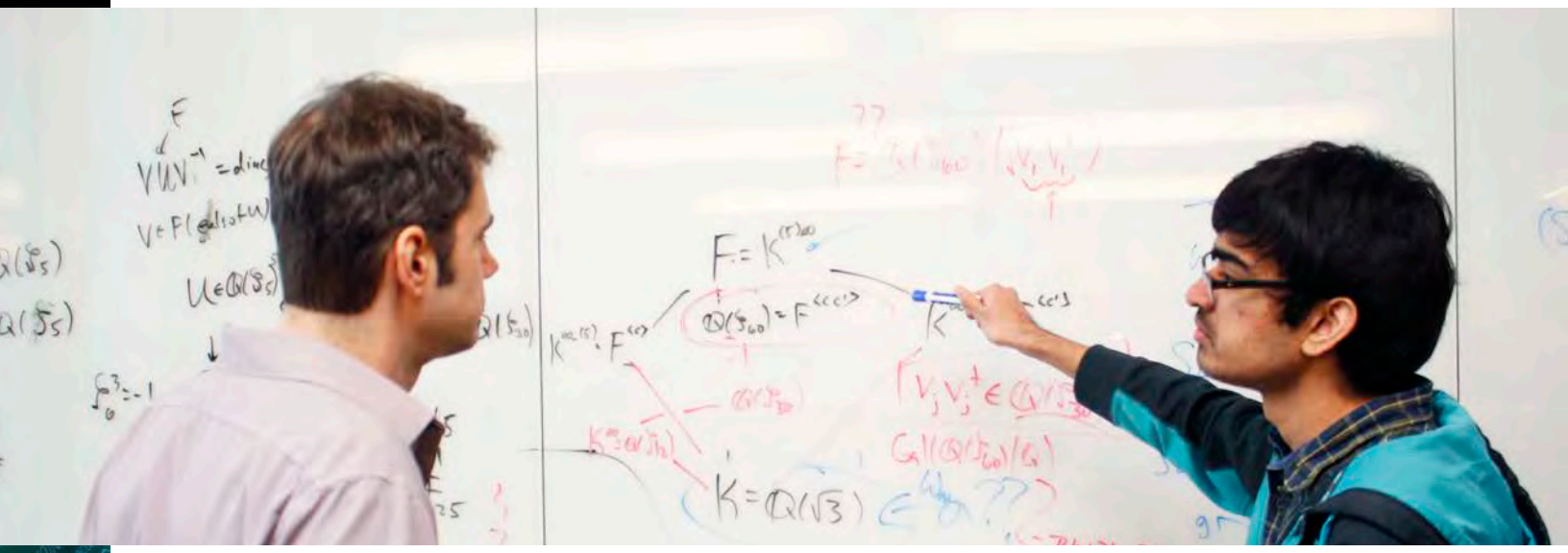
Yard is creating new compiling schemes for quantum gates and devising new error-correcting codes to ensure that quantum computers will work, despite the natural tendency for quantum information to leak into the surrounding environment.

PROBLEMS IN FAULT-TOLERANCE

Achieving fault-tolerance in classical computers is fairly simple, as they're able to employ redundancy. For example, if one or two bits in a logic gate become corrupted, the information they contain isn't lost since computers can copy and store that information multiple times.

Quantum mechanics, however, doesn't allow for the creation of identical copies. If qubits are exposed to their environment or disrupted by quantum noise, the quantum information is lost.

This presents a challenge for theorists – but not an impossible one. Yard is already able to create optimal schemes for fault-tolerant quantum gates through the "deep and subtle mathematics" of algebraic number theory. The more efficient these gates are, the fewer gates experimentalists will have to implement in the lab, saving significant resources.



JON YARD works alongside undergraduate research assistant **SANKETH MENDA.**

"You ask questions, and you try to answer them, and you keep asking questions... eventually you find an answer."

SMALL STEPS FORWARD

In Yard's own work, the real challenge is finding a way to merge these small-scale fault-tolerant systems into the greater whole. He can reason about large systems of multiple qubits, but the dimensions of those systems grow far too fast to reliably store all their information.

Ultimately, the process of invention can take some time. As Yard says, "You can't force a breakthrough – they just happen." He doesn't often see researchers sprinting down the halls screaming "Eureka!" However, small moments of discovery still happen every day. It's that very thrill – of puzzling out the next algorithm, expanding our insight into the nature of the quantum world – that pushes Yard forward.

"We're just trying to understand things," he says. "You ask questions, and you try to answer them, and you keep asking questions... eventually you find an answer."

IMAGINING THE QUANTUM FUTURE

Moving forward, Yard plans on taking a big-picture approach to tackling quantum challenges. Certain hardware implementations for a quantum computer might work better with some algorithms and error-correcting codes over others. Uncovering these optimal combinations will enable Yard to start envisioning the system architecture for a fully-fledged quantum computer. He soon hopes to collaborate with colleagues to turn mathematical theory into experimental reality.

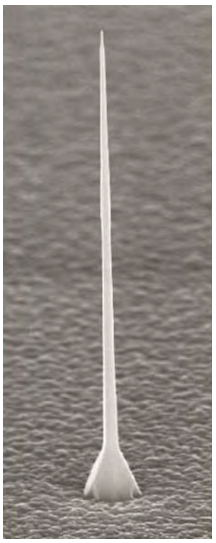
In the meantime, however, Yard continues to follow his curiosity. As he says, "Ideas emerge from studying theory." Every question asked sparks new discoveries and ideas. ■

SCIENCE HIGHLIGHTS

IQC faculty, postdoctoral fellows and students continue to conduct internationally recognized quantum information science research. Here is a sampling of their research published in academic journals.

VIOLATING BELL'S INEQUALITY WITH NANOSCALE LIGHT SOURCES

Scientific Reports 7, 1700 (2017)



A semiconductor nanowire after the growth process with unique tapered shape to efficiently extract light from the quantum matter.

MICHAEL REIMER was part of an international team that achieved the first violation of Bell's inequality in a photonic nanostructure with enhanced light extraction efficiency.

Researchers embedded highly symmetrical quantum dots – nano-sized artificial atoms that emit light – inside special nanowire structures theoretically able to create highly entangled photons with near-unity efficiency. Though the researchers did not yet reach this theoretical upper limit, they generated two orders of magnitude more entangled photon pairs than previously reported from standard quantum dot structures and conclusively violated Bell's inequality.

Entangled photon pairs primarily have applicability in quantum communications and cryptography, which use the property of entanglement – where particles are so strongly linked that one cannot describe either of them individually – to generate unbreakable encryption keys. Achieving this entanglement means that photons show strong correlations in a way that cannot be explained by hidden, local relationships; this is quantified by violating Bell's inequalities.

The high fidelities of photon entanglement achieved through this method stand to both increase the security of quantum cryptography and drastically reduce the time needed to complete quantum optics experiments.

The paper, *Bright nanoscale source of deterministic entangled photon pairs violating Bell's inequality,* was published in *Scientific Reports* on May 10.

WEB **bit.ly/bright-nanoscale-source**

New causal structures only found in the quantum world

Nature Communications 8, 15149 (2017)

Building on past research which showed that in the quantum world, certain kinds of correlations do imply causation, a team of IQC researchers discovered that there are types of causal structures unique to the quantum realm.

The research team, which included IQC faculty member **KEVIN RESCH** and PhD student **JEAN-PHILIPPE MacLEAN**, found a kind of physical mixture of causal mechanisms that act quantum-coherently with one another.

The rich new possibilities implied by this discovery could lead to new insights into understanding the relationship between causality and quantum correlations, especially relating to entanglement. Causality is a fundamental concept for those in the fields of epidemiology, genetics and social sciences, and the research sheds new light to causal relationships in a quantum world.

The paper, *Quantum-coherent mixtures of causal relations*, was published in *Nature Communications* on May 9.

WEB **bit.ly/quantum-coherent-mixtures-of-causal-relations**

SCIENCE
HIGHLIGHTS

STUDY PROVES VIABILITY OF QUANTUM SATELLITE COMMUNICATIONS

2017 Quantum Sci. Technol. 2 024009

Postdoctoral fellow JEONGWAN JIN and PhD student CHRISTOPHER PUGH prepare a quantum satellite receiver prototype onboard a National Research Council Canada (NRC) aircraft. *Photo credit: NRC*

After nearly eight years of preparation, IQC's Quantum Encryption and Science Satellite (QEYSSat) team led by **THOMAS JENNEWEIN** achieved the first demonstration of quantum key distribution (QKD) from a ground transmitter to a quantum payload circling in an aircraft overhead.

The payload was designed to conform to the size and operating restrictions of a micro-satellite, ensuring that the test was a valid proof-of-concept demonstrating the viability of the QEYSSat prototype for future satellite missions.

Currently, ground-based QKD systems rely on optical fibers limited to distances of only a few hundred kilometers. Use of satellite systems stand to expand this distance to a global scale, allowing unbreakable quantum key encryption and communication around the world.

WEB **bit.ly/airborne-demo-QKD-receiver-payload** ■

Photon triplets pave way for multi-photon entanglement

Nature Communications 8, 15716 (2017)

A team of IQC researchers including postdoctoral fellow **MILAD KHOSHNEGAR** and associate **GREGOR WEIHS** experimentally demonstrated the creation of photon triplets, correlated by time, using a quantum dot molecule. Their recorded average of 65.2 photon triplets emitted per minute is the highest detection rate so far.

To create the triplets, researchers sent picosecond pulses of light into a photonic nanowire, through a pair of quantum dots, and then into a quantum dot molecule. Using a time-tagging device and photon detectors, researchers were able to measure the photon output, confirming that the three photons were emitted at the same time, rather than being three independent events.

These results pave the way for the direct generation of three-photon entanglement in a solid-state system, which could be useful for quantum communication protocols, as well as third-party cryptography.

The paper, *A solid state source of photon triplets based on quantum dot molecules*, was published in *Nature Communications* on June 12.

WEB **bit.ly/solid-state-source-photon-triplets**

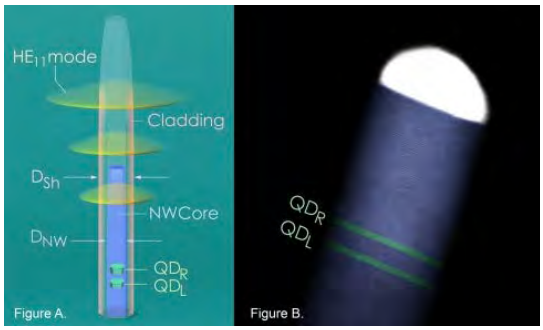


Figure A: **The schematic of a quantum dot molecule (QDM) embedded inside a clad nanowire.**

Figure B: **False-coloured scanning electron microscopy image of an InP nanowire.** ■

KAYLA HARDIE working with the LED-based spectrophotometer in the lab.

New device offers simple and affordable way to identify optical coatings in the lab

IEEE Sensors Journal (Volume: 17, Issue: 19, Oct. 1, 1 2017)

A light emitting diode (LED)-based spectrophotometer designed and implemented by IQC researchers is the first demonstration of characterizing optical coatings using a simple, automated device.

The peer-reviewed paper *Inexpensive LED-Based Optical Coating Sensor*, published in the October 1 issue of *IEEE Sensors*, was the first for undergraduate student **KAYLA HARDIE**, who developed the technology as an undergraduate research assistant in faculty member **THOMAS JENNEWEIN**'s lab. Postdoctoral fellow **KATANYA KUNTZ** and PhD student **SASCHA AGNE** were also involved in the project.

The device is able to identify coating types through the use of ten rotating LEDs and a silicon photodetector that measures how the sample reflects light on a spectrum from ultraviolet to near-infrared. Unlike most commercial optical filters, the device can block out all wavelengths outside a specified range. It's also inexpensive, portable, user-friendly and simple to build, demonstrating its usefulness in labs or as a teaching tool.

WEB **bit.ly/LED-based-optical-coating-sensor** ■

Experiment finds way to increase photon efficiency for quantum communications

Phys. Rev. Applied 8, 054015 (2017)

A team of IQC researchers demonstrated a new type of on-demand single photon generator that can shape photons to increase their efficiency when used in a quantum network.

"Our results show an important proof-of-principle of an enabling technology for quantum networks, which is easily extensible to other types of physical systems beyond superconductors," said faculty member **CHRISTOPHER WILSON**, principal investigator of the Engineered Quantum Systems Laboratory (EQSL). Former postdoctoral fellow **POL-FORN DÍAZ**, former master's student **CHRISTOPHER WARREN** and PhD students **CHUNG WAI SANDBO CHANG** and **VADIRAJ ANANTHAPADMANABHA RAO** also contributed.

The new photon generator is a superconducting circuit comprised of two main parts. The first, a superconducting qubit, acts like an artificial atom that emits microwave light. The second is a superconducting transmission line that carries electrical signals through the circuit.

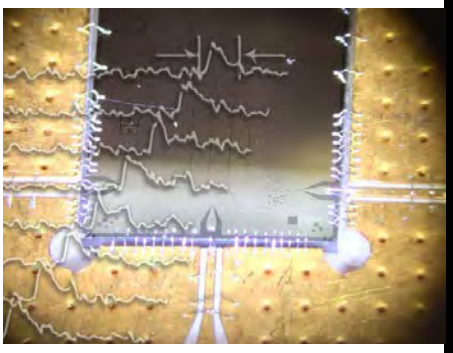


Image of the superconducting circuit used in the experiment. The overlay shows measured single-photon pulses.

The ability to produce shaped photons is important for efficient absorption of photon pulses by distant nodes of a quantum network," said Wilson. "This work further demonstrates how quantum microwaves are a resource for future quantum communication networks."

WEB **bit.ly/on-demand-mw-gen-shaped-photons** ■

SCIENCE HIGHLIGHTS

CONFERENCES & WORKSHOPS

Undergraduate School on Experimental Quantum Information Processing

Last summer, 24 undergraduate students from 12 countries, all with a passion for engineering, physics and computer science, had the opportunity to explore the field where all three topics intersect: quantum information science. From May 29 to June 9, they participated in the Undergraduate School on Experimental Quantum Information Processing (USEQIP), a fully funded two-week boot camp introduction to the study of quantum information science. Through lectures from leading quantum researchers and thirty hours of hands-on lab experience, students received an inside look at what it's like to pursue graduate studies in quantum information. ■

Women in Physics Canada 2017

Early career scientists came together from July 26 to 28, for the 6th annual Women in Physics Canada (WIPC) conference hosted at IQC. While primarily a research conference, it's also designed to promote diversity and bring together early career scientists.

Through panels and workshops, researchers like IQC postdoctoral fellows **KATANYA KUNTZ** and **RAZIEH ANNABESTANI** shared their stories and challenges, hoping to guide other young female scientists on their paths forward in a currently male-dominated field.

Common themes emphasized the importance of strong female role models and support networks, positive relationships with academic supervisors and regular self-care in the face of discrimination and adversity. IQC postdoctoral fellow **CHRIS HERDMAN** also spoke at the conference, emphasizing that the overrepresented can still help to promote change by encouraging others to join the conversation.

WEB **bit.ly/women-in-physics-support-networks** ■

QCSYS

Quantum Cryptography School for Young Students

For the 9th year running, IQC hosted 40 secondary school students for the Quantum Cryptography School for Young Students (QCSYS), an intense eight-day enrichment program. From August 11 to 18, participants enjoyed a blend of lectures and hands-on experiments focused on quantum cryptography — a cutting-edge field that utilizes the fascinating laws of quantum mechanics to develop unbreakable encryption. When they weren't transmitting quantum keys or receiving one-on-one mentorship from IQC researchers, students got to experience living in a university residence with classmates from around the globe. The program aims to encourage these high-achieving students to pursue future careers in the field of quantum science. ■

QUANTUM IN IQALUIT

In July, researchers from IQC left their labs behind to venture into the midsummer tundra of Iqaluit, the capital of Canada's newest territory, Nunavut.

Like any scientific gathering, "Quantum in Iqaluit" included presentations and question periods; but it also blended cutting-edge science with ancient traditions, fostering a cultural exchange of ideas. Residents of Iqaluit learned about quantum science and concepts like Schrödinger's cat through IQC's travelling exhibit, *QUANTUM: The Pop-Up Exhibition*. For the researchers, whose work seeks to understand natural phenomena at the subatomic level, exposure to Inuit interpretations of nature provided new perspectives on what they do as scientists.

"I don't think I've ever been to a place that has inspired me to think so much about how things work — how people live, how they survive, how they thrive," said **KEVIN RESCH**, faculty member and interim executive director of IQC. "People will be talking about this meeting for a long time — not just for the scientific ideas we discussed, but for the experiences we shared."

When they weren't talking quantum, researchers took part in Inuit traditions, cheered on local throat singers and climbed over rugged tundra in a group scavenger hunt through Sylvia Grinnell Territorial Park.

The conference also served to commemorate the 15th anniversary of IQC and the legacy of founding director **RAYMOND LAFLAMME**. It also marked the 20th anniversary of a paper by **ALEXEI KITAEV** that helped establish quantum computing as a real-world possibility.

Among the researchers in attendance were Kitaev's peers and longtime collaborators of Laflamme's, including **WOJCIECH ZUREK**, **JEFF KIMBLE**, **HARRY BUHRMAN**, **JUAN PABLO PAZ** and others who have advanced quantum information science over the past several decades.

WEB **bit.ly/quantum-in-iqaluit** ■

SCIENCE HIGHLIGHTS

Quantum Innovators

New this year, IQC offered two different Quantum Innovators workshops to bring together the most promising young postdoctoral fellows and early career researchers.

Quantum Innovators in Computer Science and Mathematics (September 18-22) hosted 15 young computer scientists and mathematicians working on theoretical aspects of computation and quantum information. Quantum Innovators in Science and Engineering (October 2-5) gathered 19 experimentalists and theorists studying quantum physics and engineering. Participants in both groups explored the frontier of quantum information science and technology by sharing their own research and learning about the work of their peers.

The four-day workshops held at IQC are partly funded by the Canada First Research Excellence Fund (CFREF) as part of the Transformative Quantum Technologies (TQT) research initiative.

(left) Quantum Innovators in Computer Science and Mathematics
(right) Quantum Innovators in Science and Engineering ■

Schrödinger's Class

Last Fall, teachers once again became students at Schrödinger's Class – a free workshop on quantum mechanics and technology. From December 8 to 10, 32 participants attended keynote lectures from IQC faculty and engaged in hands-on activities designed to help them integrate quantum technology into the current teaching curriculum. They toured IQC labs, used the double-slit experiment to measure the width of a hair and built their own quantum cryptography systems using coins and boxes. Teachers came away with the knowledge to discuss cutting-edge advances in the quantum field, as well as ready-to-go activities and lesson plans to take back to their classrooms. ■

UPCOMING CONFERENCES

» **Undergraduate School on Experimental Quantum Information Processing (USEQIP)**

May 28-June 8, 2018

» **Quantum Cryptography School for Young Students (QCSYS)**

August 10-17, 2018 ■

VISITS & TOURS

Welcome to IQC

Current and future partners come to learn about the quantum research that happens at IQC, tour facilities and explore potential opportunities for collaboration. During the spring and fall terms, IQC welcomed:

35
visitors from academic institutions

70+
government officials representing **18** delegations

390+
industry visitors on behalf of **55** companies ■

IQC OUTREACH

#InEveryClass

On May 26, Innovation150 hosted a pop-up science expo at Cathedral High School in Hamilton, Ontario. More than 1,700 students came to interact with and learn from 11 of Canada's largest science organizations. The pop-up experience brought together leading scientists, cutting-edge technologies and opportunities to celebrate Canadian ideas and ingenuity.

Senior Manager, Scientific Outreach, **MARTIN LAFOREST**, Scientific Outreach Officer **ELECTRA ELEFTHERIADOU**, Manager, Special Projects **ANGELA OLANO** along with IQC students **JEREMY FLANNERY**, **SIMON DALEY** and **THOMAS ALEXANDER** were on hand for demonstrations of the superconducting levitating train and to tour expo participants through *QUANTUM: The Pop-Up Exhibition*.

PHYSICS DAYS

In partnership with the Department of Physics and Astronomy in the Faculty of Science, IQC hosted more than 300 senior high school students from six schools across Ontario from December 7-18. Students split their time on campus between the physics and astronomy department and IQC, where they learned about quantum through hands-on activities in the lab with IQC students **PATRICK DALEY**, **JEREMY FLANNERY**, **NAIRONG HOU**, **SHAYAN-SHAWN MAJIDY**, **RAMY TANNOUS**, **ANNELISE BERGERON**.

IQC OUTREACH

Sharing quantum in Canada and beyond

Senior Manager, Scientific Outreach, **MARTIN LAFOREST** was on the road again—this time sharing quantum with fellow Canadians across the country and abroad. Stops included: TELUS Spark, Calgary for Beer + QUANTUM, the Université de Sherbrooke in Sherbrooke, Québec, and London, England for a public talk at Canada House. ■

TEACHING TEACHERS QUANTUM

MARTIN LAFOREST and Scientific Outreach Officer **ELECTRA ELEFTHERIADOU** shared the quantum world with teachers, giving them the tools to teach quantum, through several workshops including:

- Ontario Association of Physics Teachers (OAPT) Conference in Toronto on May 12;
- Perimeter Institute's EinsteinPlus workshop in Waterloo on July 11;
- and a special two and a half day workshop for the Physics Teachers Resource Agents of the American Associations of Physics Teachers in Cincinnati from July 19-21. ■

Lloyd Auckland Invitational Mathematics Workshop

Quantum computing and cryptography was the focus of an afternoon workshop for 60 female high school students as part of their programming at the Lloyd Auckland Invitational Mathematics Workshop, hosted by the Centre for Education in Mathematics and Computing (CEMC) at the University of Waterloo on May 30. **MARTIN LAFOREST** guided the group through hands-on activities demonstrating the principles of quantum mechanics. ■

TAKING QUANTUM BEYOND BORDERS

In November 2017, IQC's *QUANTUM: The Pop-Up Exhibition* made its way across Europe, making stops in Berlin, Delft, London and Brussels to showcase the power of quantum technologies and celebrate the contribution by Canadian scientists to this rapidly growing research field.

IQC alumnus **JOHN DONOHUE** was on hand in Berlin to guide visitors through *QUANTUM: The Pop-up Exhibition*, and participated in a panel on quantum in celebration of Berlin Science Week.

"We often hear from people that quantum science is intimidating," said **TOBI DAY-HAMILTON**, director of communications and strategic initiatives at IQC. "From the beginning, our goal in developing *QUANTUM: The Exhibition* was to engage people of all ages in a fun and unique way. A lot of amazing research takes place right in our own backyard and we want to share this great work with the world."

Manager, Special Projects **ANGELA OLANO** led the European tour of *QUANTUM: The Pop-Up Exhibition*. The portable version of the quantum experience was designed to accommodate demand at events and festivals, and incorporates popular interactive activities, games and videos from the larger exhibit, taking up less than 10 percent of the space. ■

Around the INSTITUTE

From theory to experiment

Master's student PROFILE: **ANNELISE BERGERON**

"If you think you understand quantum mechanics, you don't understand quantum mechanics."

The famous Richard Feynman quote is daily inspiration for master's student **ANNELISE BERGERON**, who is fascinated by the counter-intuitiveness of quantum mechanics. "It's learning about a whole new world, with a whole new set of rules," she said, describing the intrigue of the field.

Hailing from the state of Louisiana, Bergeron credits an inspirational high school chemistry teacher with first piquing her interest in theoretical physics. By the time she was ready to pursue graduate studies, she had honed her focus in on the experimental side of quantum information.

"I was excited to dive into the experimental side of research," said Bergeron. "IQC seemed like the perfect place for me to develop my skills and gain a holistic approach to quantum research."

Continued on next page

Around
THE INSTITUTE

From theory to experiment *continued from previous page*

In the Coherent Spintronics Lab group led by faculty member **JONATHAN BAUGH**, Bergeron's research focuses on building superconducting semiconductors for topological quantum computing. She's working towards engineering an inherently topologically protected quasi-particle called a Majorana Fermion.

The inherent protection from environmental noise and decoherence caused by electrical disturbances and other instabilities is an advantage over other schemes for quantum information processing.

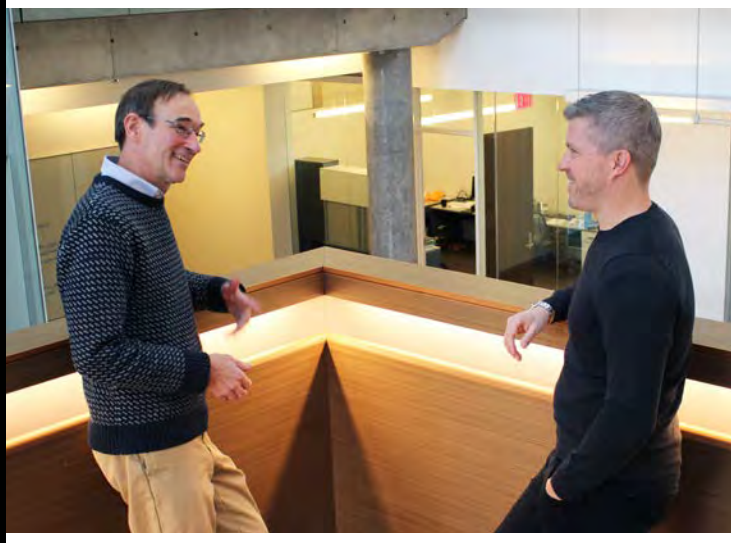
"A quantum computing scheme with this level of protection provides an edge for a successful computational platform," she said. "Theoretically, it's possible. Now we're working on implementing this in the lab." In addition to the potential for quantum computing with Majorana fermions, Bergeron acknowledges the exciting possibilities that these devices open up for materials science. "We can look at the way a semiconductor inherits superconducting properties when in proximity to a superconductor, and how this affects quantum transport."

Outside of the lab, Bergeron's interests are noticeably diverse. She is a self-described foodie with a passion for dance, music and the arts. She cycles competitively and builds furniture, tackling all kinds of construction projects from bookshelves to daybeds.

But what gives her the most sense of satisfaction each day is her research.

"I'm working on the verge of something new, which is really exciting," she says. "The gain in quantum computing research momentum over the past fifteen years is unique to the period of time that I'm growing up in, and I want to be a part of that race." ■

ACTIVITIES



RAYMOND LAFLAMME, founding director of IQC and John von Neumann Chair in Quantum Information and EDWIN OUTWATER, music director laureate of the Kitchener-Waterloo Symphony, discuss the collaboration behind *Quantum Etude*. ■

CONNECTING QUANTUM AND MUSIC

The first *Entangled: The Series* talk, QUANTUM + music, was held October 3 with **RAYMOND LAFLAMME**, founding director of IQC and John von Neumann Chair in Quantum Information and **EDWIN OUTWATER**, music director laureate of the Kitchener-Waterloo Symphony.

Moderated by **MIKE FARWELL**, Laflamme and Outwater discussed their collaboration *Quantum Etude*, a musical performance that integrates quantum physics to create a surprisingly random performance piece. The music of *Quantum Etude* encapsulates key concepts in quantum mechanics using both musical form and the performance method itself.

WEB **bit.ly/quantum-and-music** ■

ANNOUNCEMENTS & AWARDS

PhD STUDENT AWARDED VANIER SCHOLARSHIP

DANIEL GRIMMER was awarded the Natural Science and Engineering Research Council (NSERC) Vanier Canada Graduate Scholarship valued at $150,000 over three years. The prestigious scholarship acknowledges Grimmer's research excellence in decoherence – a serious obstacle to building a universal quantum computer.

The award also recognizes Grimmer's instrumental leadership in the Physics Graduate Student Association (GSA), strengthening ties between the research communities of IQC, the University of Waterloo's Department of Physics and Astronomy and the Perimeter Institute for Theoretical Physics.

Grimmer was also awarded the President's Graduate Scholarship (PGS) by the University of Waterloo, provided to outstanding graduate students who hold major competition-based government scholarships. ■

THESIS DEFENCE

Congratulations to students who defended their thesis during the Spring and Fall terms, including:

SASCHA AGNE, PhD
PAULINA CORONA, PhD
JIE LIN, MSc
BENJAMIN LOVITZ, MSc
CHRISTIAN MASTROMATTEI, MSc
COREY RAE MCRAE, PhD
JOCHIM NSOFINI, PhD
HELEN PERCIVAL, MEng
CHRISTOPHER PUGH, PhD
ALLISON SACHS, MSc
YONGCHAO TANG, PhD
ZIMENG WANG, MSc
CHRISTOPHER WARREN, MSc ■

Raymond Laflamme recognized for research excellence

IQC faculty member and founding director **RAYMOND LAFLAMME** was honoured with two prestigious awards:

- On September 14, Laflamme was named the Mike and Ophelia Lazaridis John von Neumann Chair in Quantum Information. The $8 million investment from the University of Waterloo, in collaboration with **MIKE** and **OPHELIA LAZARIDIS**, will support Laflamme's continued research on error correction in quantum systems – critical to the development of a quantum computer and other robust quantum technologies.
- Her Excellency the Right Honourable **JULIE PAYETTE**, Governor General of Canada, appointed Laflamme to the Order of Canada for his significant scientific and leadership contributions to the country on December 29. ■

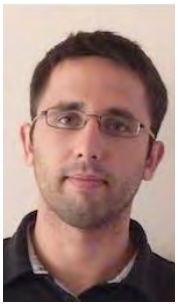
Around
THE INSTITUTE

Canadian Space Agency awards IQC $1.5M for encryption mission

On December 19, the Canadian Space Agency (CSA) awarded $1.5 million to IQC to lead the science of a mission called the Quantum Encryption and Science Satellite (QEYSSat), which will protect the communications and data of Canadians on Earth and in space.

"The development of revolutionary technologies like quantum encryption will provide Canadians with security, safety, reliable government services and protection of their privacy. This investment enables the University of Waterloo to advance Canada's technological and scientific expertise in quantum technologies. It creates new opportunities to develop a highly qualified workforce in Canada and opens new markets and commercial opportunities around the world," said The Honourable **NAVDEEP BAINS**, Minister of Innovation, Science and Economic Development. ■

PhD student earns IQC Achievement Award



DUSAN SARENAC, PhD student, was recognized in December with the IQC Achievement Award for his collaborative work with faculty members **DAVID CORY** and **DMITRY PUSHIN** on a method to prepare beams consisting of a lattice of orbital angular momentum states coupled to two-level systems.

The award is given to an IQC student who has made an exceptional contribution to quantum information research. ■

IQC RESEARCHERS RECEIVE CFI INFRASTRUCTURE FUNDING

On October 12, faculty members **KYUNG SOO CHOI** and **THOMAS JENNEWEIN** were awarded funding for infrastructure to support their research through the Canada Foundation for Innovation (CFI) Fund.

Choi received $960,000 for his research on photonic quantum circuits and the integration of atomic and solid-state quantum systems. His work focuses on the development and application of the most advanced techniques in cold atom physics and quantum optics to probe the fundamental nature of the quantum world.

Jennewein received $338,000 to fund the creation of a Quantum Communications Payload Operations Centre. Jennewein is the principal investigator of the Quantum Encryption and Science Satellite (QEYSSat) project that aims to demonstrate the generation of encryption keys through the creation of quantum links between ground and space, and also to conduct fundamental science investigations of long-distance quantum entanglement. ■

Norbert Lütkenhaus named Fellow of the American Physical Society

Faculty member **NORBERT LÜTKENHAUS** was named a Fellow of the American Physical Society (APS) on October 17. He was recognized for his "pioneering theoretical contributions to the fields of quantum secure communications and optical quantum information processing."

Lütkenhaus' research focuses on finding advantageous quantum communication protocols, including secure Quantum Key Distribution (QKD). He aims to bridge the gap between a theoretical computer-sciences based approach to quantum communication and its physical implementation. ■

COURSES

SPRING 2017

QIC 891
Topics in Quantum Safe Cryptography

QIC 890
Introduction to Noise Processes

FALL 2017

QIC 710
Quantum Information Processing

QIC 820
Theory of Quantum Information

QIC 880
Nanoelectronics for Quantum Information Processing

QIC 890
Solid State Photonic Devices

QIC 890
Modern Quantum Optics and Nanophotonics ■

ARRIVALS

Students

Tina Dekker
Patrick Daley
Han (Vincent) Weng
Nairong Hou
Yu (Jerry) Shi
Brendan Bramman
Andrew Cameron
Michael Chen
Nikhil Kotibhaskar
Dariusz Lasecki
Richard Lopp
Pei Jiang Low
Ashutosh Marwah
Richard Rademacher
Joshua Ruebeck
Jiahao Shi
Bowen Yang
Yutong Dai
Andy (Zhenghao) Ding
Gilbert (Chung-You) Shih
Ruoxuan Xu
Sam Winnick
Petar Simidzija
Antonio Martinez
(Seyed) Sahand Tabatabaei
Evan Peters
Matthew Alexander
Jose de Ramon Rivera
Lane Gunderman
Samuel Jaques
Andrew Jena
Andrew Jordan
He (Ricky) Ren
Theodore Rogozinski
Allison Sachs
Sebastian Slaman
Nadine Stritzelberger
Ningping Cao
Erickson Tjoa

Postdoctoral fellows

Paulina Corona Ugalde
Matthew Coudron
Mark Girard
Aleksander Kubica
Tian Lan
Fereshteh Rajabi
Pooya Ronagh
Karthikeyan Sampath Kumar
Francois Sfigakis
Yongchao Tang
Pan Zheng

Staff

Taso Alkiviades
Christine Bezruki
Louise Green
Trenton McNulty
Alanna Wilson

Visitors

Qian Xue
Vinod Raj Rajagopal Muthu
Youning Li
Noah Greenberg
Anuj Shripad Apte
Austin Bradley
Daniel Eduardo Galviz Blanco
Maria Julia Maristany
Ingrid Strandberg
Benjamin Soloway
Ahreum Lee
Andy Ding
Lorenzo Catani
Ashwin Kumar
Frankie Fung
Hengameh Bagherianlemraski
Irene Lopez Gutierrez
Louisa Huang
Han Zhang
Botao Li
Hailin Yu
Zhipeng Li
Hiacheng Xuan
Dai Wei
Anton Trushechkin
Dmitry Kronberg
Zhengcheng Gu
Dawei Lu
Chi-Kwong Li
Yiu Tung Poon
Cheng Guo
Yidun Wan
Raphaël Aymeric
Shengqiao Luo
Christine Muschik
Maren Ilango
Sara Zarar Jafarzadeh
Kirill Zhernenkov
Zhengcheng Gu
HeeBong Yang
Martin Houde
Aditya Jain ■

Around
THE INSTITUTE

CONGRATULATIONS TO OUR 2017 GRADUATES

Spring Convocation

GOLAM BAPPI
MASc Electrical & Computer Engineering (Quantum Information)

YIHANG YANG
MASc Electrical & Computer Engineering

HILLARY DAWKINS
MSc Physics (Quantum Information)

SUMEET KHATRI
MSc Physics (Quantum Information)

ALEX PARENT
MSc Physics (Quantum Information)

RAZIEH ANNABESTANI
PhD Physics (Quantum Information)

JOHN DONOHUE
PhD Physics (Quantum Information)

MATTHEW GRAYDON
PhD Physics (Quantum Information)

GREGORY HOLLOWAY
PhD Physics (Quantum Information)

XIAN MA
PhD Physics (Quantum Information)

ZACHARY WEBB
PhD Physics (Quantum Information)

XINGLIANG LOU
MMath, Combinatorics & Optimization (Quantum Information)

GUILLAUME VERDON-AKZAM
MMath, Applied Mathematics (Quantum Information)

VINCENT RUSSO
PhD, Computer Science

Fall Convocation

GUIYANG HAN
MSc Physics (Quantum Information)

ALLISON SACHS
MSc Physics (Quantum Information)

JOACHIM NSOFINI
PhD Physics (Quantum Information)

CHRISTOPHER PUGH
PhD Physics (Quantum Information)

RUI PENG LIU
MMath Combinatorics & Optimization

YONGCHAO TANG
PhD Electrical & Computer Engineering (Quantum Information) ■

physicsworld TOP 10 BREAKTHROUGH 2017

Experiment named a Top Ten Breakthrough of 2017

The observation of genuine three-photon interference, conducted independently by a team of researchers at IQC and the University of Oxford, has been named one of the Top Ten Breakthroughs of 2017 by *Physics World* magazine.

The IQC experiment was published in *Physical Review Letters* describing how researchers experimentally passed three photons, which are entangled in their energy and times, through separate interferometers. This enabled them to observe genuine three-photon interference for the first time. The experiment is a result of a collaboration led by **THOMAS JENNEWEIN** between the University of Waterloo (**SASCHA AGNE**, **JEONGWAN JIN**, **KEVIN RESCH**, **JEFF SALVAIL**, **EVAN MEYER-SCOTT**), the University of Innsbruck (former IQC member **GREGOR WEIHS** and **THOMAS KAUTEN**) and Université de Moncton (former IQC student **DENY HAMEL**). ■

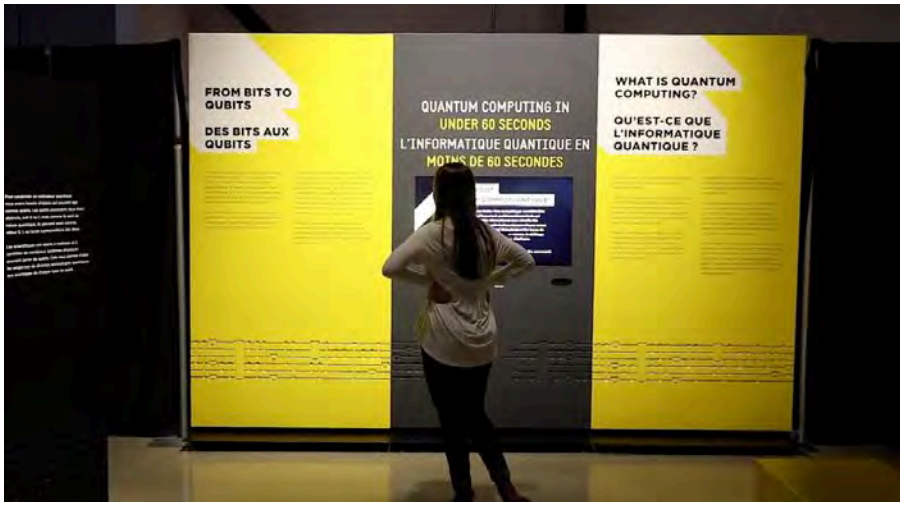
QUANTUM: THE EXHIBITION

takes centre stage in Ottawa for final stop on Canada 150 tour

The newly reopened Canada Science and Technology Museum in Ottawa was the backdrop for *QUANTUM: The Exhibition*'s final stop on its year-long Canada 150 tour. The exhibition is the world's first-ever travelling show on quantum information science and technology. Before arriving in Ottawa on December 19, it toured Canada for 18 months, making stops in Kitchener, Vancouver, Saskatoon, Calgary and Halifax.

"People across the country have experienced the quantum world through the Exhibition," said **TOBI DAY-HAMILTON**, director of communications and strategic initiatives at IQC. "We are thrilled to showcase the emerging quantum technologies that will shape our future."

At the exhibition, hands-on activities and multimedia games helped make quantum science more accessible for visitors. Guests had a glimpse into some exciting quantum technologies on the horizon and left with a new perspective on how the world works. ■



4,000
SQUARE FEET OF INTERACTIVE QUANTUM EXPLORATION

6
CANADIAN STOPS

390,422
VISITORS IN 18 MONTHS

12,724
KM TRAVELLED

THE POP-UP EXHIBITION

400
SQUARE FEET

6,881
VISITORS IN 54 DAYS

22,126
KM TRAVELLED TO 6 COUNTRIES

A NEWSLETTER FROM THE **INSTITUTE FOR QUANTUM COMPUTING**, **UNIVERSITY OF WATERLOO**, WATERLOO, ONTARIO, CANADA

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Ontario

Canada