



**Annual Report to Industry Canada**

May 1, 2009 to April 30, 2010

UNIVERSITY OF  
**WATERLOO**

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## **PREFACE**

This document is the first in a series of five annual reports that will serve as evaluations of the Institute for Quantum Computing's outputs and outcomes as they relate to the \$50 million grant from Industry Canada. This first report serves as the introduction to the series and is therefore long and detailed in setting the context for IQC's research.

This report will focus on two main evaluation issues (consistent with the new Treasury Board Policy on Evaluation effective April 1, 2009): relevance and performance. Within these two categories, the evaluation will consider:

- Appropriateness and effectiveness of the design and delivery of the research conducted by IQC
- Results achieved to date:
  - Outputs and immediate outcomes
  - Intermediate outcomes, such as the establishment of a world-class facility for QI (quantum information) research and training

According to the Grant Agreement, the University of Waterloo's Board of Governors must approve IQC's annual report to Industry Canada.

IQC's annual report will include:

- a) A statement of the institute's objectives for that year and a statement on the extent to which the institute met those objectives
- b) A list of activities undertaken with the grant
- c) A statement of the institute's objectives for the next year and the foreseeable future
- d) A description of the proposed activities for the next year to be undertaken within the context of this agreement, and a description of how the institute intends to implement them
- e) A proposed schedule for the implementation of the activities for the next year
- f) The anticipated results of those activities
- g) Results achieved in the past year in accordance with a performance measurement strategy developed by Industry Canada
- h) Risk assessment and mitigation strategies and ongoing performance monitoring strategies

About the report:

- The 2010 fiscal year runs from May 1, 2009 to April 30, 2010
- Some metrics are presented using a calendar year instead of the fiscal year – these are indicated on a case by case basis
- Headcounts:
  - Include all members that conducted research at IQC during the fiscal year and may not reflect the current headcount
    - Students are counted in the official headcount if they were registered for at least one term at UW in the 2010 fiscal year
    - Postdoctoral fellows and faculty members are counted if they conducted research at IQC in the 2010 fiscal year
    - Staff are counted as at April 30, 2010
  - If a member switched categories they are counted in their new position

## **EXECUTIVE SUMMARY**

IQC's 2009/2010 annual report to Industry Canada is the first in a series of five reports that will evaluate IQC's activities and outcomes related to the \$50-million grant from Industry Canada. This summary covers the key topics covered in the full report. The report includes a statement of IQC's objectives for the reporting year, a summary of activities undertaken with the grant, the results achieved, future objectives, a risk assessment and risk mitigation strategies.

According to the grant agreement, the University of Waterloo's Board of Governors must approve IQC's annual report to Industry Canada.

The report is an overview of the activities at IQC between May 1, 2009 and April 30, 2010. Its purpose is to demonstrate how Industry Canada's funding has allowed IQC to pursue its three strategic objectives:

1. To establish Waterloo as a world-class centre of research in quantum technologies and their applications
2. To become a magnet for students and postdoctoral fellows in the field of quantum information
3. To establish IQC as the source of authoritative information, analysis and commentary on quantum information

### **FUNDING AGREEMENT WITH INDUSTRY CANADA**

The five-year grant from Industry Canada will enable the establishment of a world-class research facility that will support the Government of Canada's science and technology strategy.

There are four key long-term outcomes of this grant: increased knowledge in quantum information, new opportunities for students to learn and apply new knowledge, Canada becomes branded as a place to conduct research in quantum technologies, and Canada becomes positioned to take advantage of economic and social benefits of research.

Industry Canada has allotted \$25 million over two years to the construction of the new Mike and Ophelia Lazaridis Quantum-Nano Centre, \$5 million over five years for the purchase of small equipment and \$20 million over five years to the following four activities:

1. Recruiting and retaining highly qualified personnel
2. Transferring knowledge
3. Supporting administrative and technical staff members
4. Purchasing materials and supplies (other than small equipment)

### **OBJECTIVES, ACTIVITIES AND EXPECTED OUTCOMES**

For the purpose of the Industry Canada grant, the achievement of IQC's three strategic objectives areas measured through activities in the following areas:

1. Conducting research in quantum information
2. Recruiting top researchers
3. Collaborating with other researchers
4. Building, facilities and laboratory support
5. Attracting, educating and training highly qualified personnel
6. Disseminating knowledge
7. Developing and communicating the IQC brand
8. Administrative support

Below is a breakdown of each activity including a brief description, expected results and highlights from the past year.

### **1. CONDUCTING RESEARCH IN QUANTUM INFORMATION**

**Description:** Foster leading-edge investigation of theoretical approaches to quantum information processing to better understand the impact of quantum mechanics for information processing and investigate potential applications. Develop approaches to QIP using photonic, nuclear and electron spins, quantum dots and superconducting technologies; study the requirements of earth-to-satellite quantum cryptography.

**Expected Results:** The creation of new knowledge leading to publications and presentations, which will foster a better understanding of QIP and its applications, ultimately leading to new technologies.

**Highlights:**

- \$23.9 million in new grants
- 123 journal articles published by IQC HQP
- Collaborative research projects or publications with researchers from 61 institutes worldwide
- John Watrous' breakthrough QIP=PSPACE

### **2. RECRUITING NEW RESEARCHERS**

**Description:** Recruit up to three new faculty members, six to 10 new postdoctoral fellows and 20 new graduate students. Continue to leverage conferences and outreach forums as recruitment opportunities.

**Expected Results:** The recruitment of top-tier faculty, postdoctoral fellows and students will create a critical mass of theoretical and experimental researchers, allowing IQC to fulfill its objectives of being a world-leading research facility, a magnet for top students and an authoritative source of analysis and commentary on quantum information.

**Highlights:**

- Five workshops with approximately 180 participants in total
- Attended four graduate fairs
- Received 104 applications to the graduate program

### **3. COLLABORATIONS WITH OTHER RESEARCHERS**

**Description:** Facilitate collaborations between quantum scientists through networks such as QuantumWorks, CIFAR's Quantum Information Program and NSERC Strategic Networks. Encourage attendance at international conferences and increased collaborations leading to co-authored papers. Organize three multi-disciplinary conferences, and increase and enhance visits to IQC by international researchers.

**Expected Results:** Strategic collaborations with top researchers will enhance IQC's international reputation, draw HQP to IQC and lead to scientific breakthroughs.

**Highlights:**

- Collaborative research projects or publications with researchers from 61 institutes worldwide
- Six grants shared between IQC faculty and non-IQC researchers
- Four newly signed memoranda of understanding with National University of Singapore, IBM, National Science Council of Taiwan, COM DEV, Indian Institute of Technology in Kanpur and National Institute of Informatics in Japan.

### **4. BUILDING, FACILITIES AND LABORATORY SUPPORT**

**Description:** Construction of the QNC remains per specifications, on time and budget, establishment of new laboratory at RAC2, continued acquisition & maintenance of RAC1 lab equipment, and preparation for expansion to QNC.

**Expected Results:** The installation and maintenance of lab equipment will facilitate high-level

experimental research at IQC.

**Highlights:**

- Construction remains within approved budget, on schedule and per UW specifications
- IQC's estimated expenditures to date are \$37 million
- Construction of cleanroom completed

**5. ATTRACTING, EDUCATION AND TRAINING HIGHLY QUALIFIED PERSONNEL**

**Description:** Roll out the graduate program, establish an open house for graduate students and enhance the prominence and content of graduate studies page on IQC website.

**Expected Results:** The graduate program will help IQC be a magnet for students, and the open house and website will be valuable recruiting tools to attract the brightest prospective students.

**Highlights:**

- Approval of the collaborative graduate program by the Ontario Council of Graduate Studies
- 9 potential new courses for the 2010-2011 academic year
- 45 external achievement awards to current graduate students
- 61 per cent of current graduate students have a GPA of 90 per cent or higher
- 60 applications to faculty positions, 119 applications to postdoctoral fellowships

**6. DISSEMINATING KNOWLEDGE**

**Description:** The full redesign of the IQC website, currently in progress, will improve the institute's outreach strategy, capabilities and goals. Further, IQC will organize meetings, workshops and other outreach initiatives ranging from public lectures to specialized conferences.

**Expected Results:** Increased outreach and information dissemination efforts will help IQC achieve its strategic objective of becoming the source of authoritative analysis and commentary on QIP.

**Highlights:**

- Five workshops with approximately 180 participants in total
- 160 academic visitors, 32 business visitors and 6 government visitors
- 58 external presentations delivered by faculty members

**7. DEVELOPING AND COMMUNICATING THE IQC BRAND**

**Description:** Assemble the full communications and outreach team by August 2010 to design and implement the communications and outreach roadmap. Lay the groundwork for branding including focus groups, market research, etc. Complete the web redesign.

**Expected Results:** Creation of a long-term strategy to fulfill the strategic objective of becoming the authoritative source of analysis and insight on quantum information.

**Highlights:**

- Growth of the Communications and Outreach team from one to three in November of 2009 and eventually five by July 2010
- Website redesign currently underway and due for launch in July 2010

**8. ADMINISTRATIVE SUPPORT**

**Description:** Provide researchers and students with the professional support needed to pursue leading-edge research in quantum information.

**Expected Results:** Develop best practices for financial standards, processes and documentation.

**Highlights:**

- Presented the 10-year financial sustainability plan to the Board of Directors
- Creation of the institute's first comprehensive budget package
- IT outsourcing to focus on value-added services

# OVERVIEW OF IQC

Harnessing the forces of nature has historically led to important and lasting changes to society.

Learning to control fire, steam, electromagnetism and atomic nuclei are some of the most compelling examples of humankind's growing understanding of the natural order.

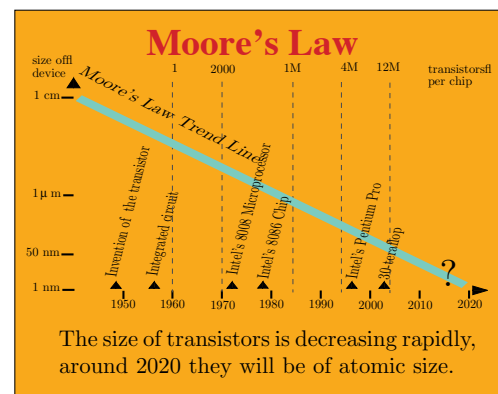
What forces of nature remain untamed? What scientific breakthroughs have yet to be made?

Computers are never as fast as we want them to be. This is not a new realization. Since the invention of electronic computers in the 1950s, scientists and engineers have been working to build faster, better versions. In trying to create more sophisticated computers, engineers determined that information could be processed faster by making transistors smaller.

In 1965, Gordon Moore, co-founder and former CEO of the Intel Corporation, observed that the size of transistors decreased by a factor of two every 18 to 24 months. He predicted that this steady shrinking of transistors would continue to hold true in the future.

Few people took Moore's Law seriously at the time, but we now know it was valid throughout the 1970s, 1980s, 1990s and into today.

Intel recently predicted that this principle should hold true for another 10 years, until the miniaturization of transistors hits a threshold. Moore's Law predicts that by the year 2020 we will have transistors the size of individual atoms.



The progress of technologies toward a smaller size is true not only for information processing devices, but also for a broad variety of applications from the cosmetics industry to molecular electronic switches. Nanotechnology involves the fabrication, study and manipulation of structures having sizes in the range of one to 100 nanometres<sup>1</sup>. This realm bridges the important gap between atoms/molecules (which range in size from less than one to several nanometers) and bulk materials. The behaviours of bulk materials are adequately described by what we call the "classical" rules of physics. At the atomic scale, however, we need to use a different set of rules to describe the behaviour of light and matter: quantum mechanics.

Quantum mechanics was discovered early in the 20<sup>th</sup> century, but scientists have only recently begun to understand how much more powerful these laws are than classical laws.

As transistors shrink, quantum effects will inevitably come into play, and we will need to start using quantum rules to describe them. If we don't, our computers will become increasingly unpredictable as they continue to decrease in size. By understanding and controlling quantum systems, we will be able to harness quantum effects and open the door to a new, and very powerful, realm of information processing.

The quantum information program will allow us to exploit quantum effects to our advantage rather than regarding them as limitations. Quantum behaviour produces novel properties with no counterparts in today's computers. The laws of quantum behaviour allow for systems to be in a multitude of states at once, thus achieving incomparable parallelism. This property allows us to solve mathematical problems once thought to be intractable, to develop unbreakable encryption of information, to build time-keeping

<sup>1</sup> A nanometre (nm) is a billionth of a metre, or a thousandth of a micron or micrometre (mm)

devices with unparalleled precision, to make ultra-sensitive detectors with tremendous accuracy, and much more.

Harnessing quantum mechanics will lead to transformational technologies that will produce a revolution in the economy of the 21st century — one in which the manipulation of molecules and atoms will be utilized in daily work and life.

IQC was created to take advantage of this extraordinary opportunity. The institute's vision, mission and fundamental strategic objectives are:

### **VISION**

Harnessing quantum mechanics will lead to transformational technologies that will benefit society and become a new engine of economic development in the 21<sup>st</sup> century.

### **MISSION**

Our mission is 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 of research in quantum technologies and their applications
2. To become a magnet for students and postdoctoral fellows in the field of quantum information
3. To establish IQC as the source of authoritative information, analysis and commentary on quantum information

The institute was established in October 2002, with a complement of five researchers from the University of Waterloo Faculties of Science and Mathematics. During 2010, the institute was home to:

<b>18</b>	Faculty
<b>1</b>	Research Assistant Professor
<b>25</b>	Postdoctoral Fellows
<b>17</b>	Administrative Support Staff
<b>63</b>	Graduate Students
<b>11</b>	Long-term Visitors
<b>2</b>	Graduate Research Assistants
<b>15</b>	Undergraduate Research Assistants



## **THE ROAD AHEAD**

Imagine a future in which computers and other everyday devices harness the peculiar and amazing laws of quantum mechanics. Imagine information processors of unprecedented power, global communications protected by ultra-secure cryptography, and giant leaps forward in biomedical research and other crucial fields.

Led by the Institute for Quantum Computing, Canada is poised to be at the forefront of the quantum information revolution. Over the past decade, Waterloo has quickly emerged as a world-class centre for research and innovation, thanks in part to IQC's mission of attracting the world's leading researchers in quantum information science. To ensure Waterloo and Canada become world-leaders in this emerging field, IQC has rapidly built a critical mass of elite faculty, students, visiting researchers and world-class facilities.

The focus in the coming year will be on cementing the research strength of IQC by attracting the highest calibre of researchers to the institute in order to strengthen its status as a world-class centre of quantum information research. The completion of two new buildings — Research Advancement Centre 2 (RAC2) and the Mike and Ophelia Lazaridis Quantum-Nano Centre (QNC) — will provide the essential tools to allow the science and engineering to be developed, to foster an atmosphere of scientific exchange and to be a recruiting tool.

IQC is implementing a strategy to attract the best students in order to build a large base of researchers to progress to postdoctoral fellowships and beyond. The institute has a long-term target of 30 faculty members, 50 postdoctoral fellows and 125 students. The road to achieving these goals will include hosting a series of student-targeted summer schools, workshops and tours. Additionally, a new collaborative graduate program with three faculties from the University of Waterloo will begin in Fall 2010. The development of a new communications and outreach program and new strategies in information technology and finance are also underway.

By harnessing the quantum world, IQC researchers will develop computers of unprecedented power, encrypt information with unbreakable security and discover a range of quantum-enabled devices that will transform our economy and society.

The quantum revolution has begun, and IQC intends to lead the charge.

## **RESEARCH FOCUS**

The research at IQC focuses on quantum information science and technology, in particular on how the laws of quantum mechanics can be used to compute and communicate or as the engine of a new generation of sensors and includes both theoretical and experimental components. In each line of research, fundamental issues and potential applications are investigated through theoretical study. These applications are then put to the test by demonstrating that the necessary quantum effects can be harnessed, forming the building blocks for quantum information science and technology and providing its experimental foundation. Finally, some building blocks are integrated to provide an important step towards the commercialization of the technologies.

The lines of research mentioned above can be broken into seven themes that outline the day-to-day research at IQC.

1. Quantum Information and Communication
2. Quantum Algorithms and Complexity
3. Quantum Cryptography
4. Quantum Error Correction and Fault-Tolerance
5. Optical Quantum Information Processing
6. Spin-based Quantum Information Processing
7. Nanoelectronics-based Quantum Information Processing

## **QUANTUM INFORMATION AND COMMUNICATION**

The theory of quantum information and communication includes the study of the fundamental properties and capabilities of quantum information storage and communication. This knowledge underlies all the applications of harnessing quantum mechanics for the purposes of information processing as well as approaches for implementing quantum information processors. Whereas classical computers operate on binary “bits,” quantum computers utilize quantum bits (qubits), which are not subject to the everyday laws of classical mechanics, and therefore exhibit some remarkable and counterintuitive properties. One such property, “entanglement” of two or more qubits, gives rise to what Einstein called “spooky action at a distance.” A consequence of this entanglement is “super-dense” coding, whereby two bits of classical information can be squeezed into a single qubit of quantum information, such that the two encoded bits can later be perfectly recovered from the packed qubit. Another consequence is quantum teleportation, whereby a qubit in an arbitrary, unknown state can be transmitted over a distance — or teleported — by sending only two bits of classical information.

Researchers are exploring many different ways of packing classical information onto qubits, and vice-versa. IQC faculty member Ashwin Nayak discovered the limit of super-dense quantum coding in an important paper on “random access” codes. Recently, some focus has shifted from packing information into qubits to passing information through quantum channels. The capacity to send classical data simultaneously through a collection of quantum channels can actually increase beyond the sum of the individual channel capacities, thanks to the use of entanglement. IQC researcher Debbie Leung was among the researchers who contributed to the refutation of the long-standing “additivity conjecture” for quantum channel capacities. Norbert Lütkenhaus specializes in the theory of quantum computation and its quantum optical implementations. Richard Cleve and John Watrous have made significant discoveries that demonstrate an exponential improvement in communication when using qubits over classical bits.

## **QUANTUM ALGORITHMS AND COMPLEXITY**

The field of quantum computing was kick-started in the 1990s when it was discovered that many computational tasks could be tackled more efficiently with quantum algorithms and protocols than with their classical counterparts. The Feynman-Deutsch principle, proposed in the 1980s, said that every finitely realizable physical system can be perfectly simulated by a universal quantum computer operating by finite means. The first major breakthrough came when MIT researcher Peter Shor unveiled a quantum algorithm that could efficiently factor large numbers — an intractable problem for classical computers. Since then, an increasing number of computational tasks, including resource allocation optimization and “needle-in-haystack” search problems, can be performed substantially faster with quantum algorithms than with classical ones.

Whereas the creators of quantum algorithms focus on what quantum computers can achieve, the study of complexity examines what they cannot do. Quantum computational complexity studies the notion of difficulty, as it pertains to the “hardness” of problems for both classical and quantum computers to solve. Through the notion of NP-completeness, complexity theory has shown that wide swaths of these “needle-in-the-haystack” problems are equivalent to one another: an efficient algorithm for one implies an efficient algorithm for all.

Pioneering work in this field was done in the early 1990s by a number of current IQC faculty members including John Watrous, Richard Cleve, Michele Mosca and Ashwin Nayak. More recently, IQC researcher Ben Reichardt has conducted leading research in fault-tolerance and quantum algorithms. Watrous and collaborators achieved a major breakthrough in 2009 when they resolved a decade-old complexity problem by proving the equivalence of two collections of computational problems called QIP and PSPACE.

## **QUANTUM CRYPTOGRAPHY**

The “Heisenberg Uncertainty Principle,” may be mathematically formalized and quantified by theorems known as information-disturbance tradeoffs. By exploiting such tradeoffs, one can devise two-party cryptographic communication protocols, such that any adversarial third party who attempts to observe or otherwise tamper with the transmitted quantum systems is detectable. Quantum Key Distribution (QKD) is one such protocol, which enables the two parties, who are assumed initially to possess short binary numbers, known as “keys,” to generate a much longer shared secret key (if no eavesdropper is detected) that is statistically independent of the initial keys, even though the communication channel between the two parties is under the complete control of the adversary. Such secret key generation is impossible to achieve without exploiting quantum effects. The two parties can then use the secret key to communicate securely, for example, to send and receive secret messages that are encoded and decoded with the secret key, using standard techniques for encryption.

IQC is home to “Alice,” a QKD receiver consisting of a photon detector connected to a standard computer; her counterpart, “Bob,” is housed at Waterloo’s Perimeter Institute for Theoretical Physics. Alice and Bob receive photons emitted from a laser. Alice and Bob can generate a secret key by measuring successive entangled photon-pair halves, whose measurement statistics will bear the fingerprint of any attempt by “Eve” or anyone else to learn the secret key. Researchers at IQC have studied other facets of quantum cryptography as well, including quantum money and quantum private channels.

IQC researchers Norbert Lütkenhaus and Thomas Jennewein have contributed leading theoretical and experimental research to the field of quantum cryptography. IQC faculty member Gregor Weihs investigates the theory, physical building blocks, and engineering of quantum cryptography. Researchers

benefit from collaborations with leading experts in cryptography, security, and quantum information theory in the University of Waterloo's departments of Combinatorics and Optimization, Computer Science, Electrical and Computer Engineering, the Centre for Applied Cryptographic Research and the Privacy Research Group.

### **QUANTUM ERROR CORRECTION AND FAULT-TOLERANCE**

One of the biggest hurdles faced by quantum computing researchers is decoherence — the tendency of quantum systems to become disturbed by “noise,” which leads to errors. This vulnerability of quantum systems to disturbance has necessitated the field of Quantum Error Correction, which is concerned with overcoming errors caused by decoherence, as well as by faulty quantum gates and measurements. The techniques for correcting errors are themselves vulnerable to noise, so it is crucial to develop tools for fault-tolerant correction of quantum errors. This includes the use of quantum error correcting codes, which is fundamental to the practical realization of quantum computation. Although error correction is not exclusively a quantum computing concern (classical computation and communication are also susceptible to errors needing correction), quantum computing introduces new challenges and opportunities. IQC possesses a critical mass of leading pioneers in various aspects of quantum error correction and fault-tolerance, including experimental error characterization and implementation of error correction techniques. IQC Director Raymond Laflamme is one of the pioneers of quantum error correction and the theory of fault-tolerant quantum computing. Laflamme has also collaborated with David Cory on the first experimental testing of quantum error correction in liquid-state nuclear magnetic resonance. Ben Reichardt's work in algorithms and fault tolerance brings together ideas from theoretical computer science and quantum physics. Frank Wilhelm has led valuable investigations into decoherence theory, quantum noise and control theory. Debbie Leung and collaborators were the first researchers to explore approximate quantum error correction, and Leung has done leading work in measurement-based quantum computing.

### **OPTICAL QUANTUM INFORMATION PROCESSING**

Quantum information processing was first implemented with particles of light (photons) and with trapped ions, and subsequent proposals included other approaches using trapped atoms. In quantum optics, photons are used to carry quantum information. A commonly used attribute of photons to encode this information is polarization. Each photon's polarization can, for example, be horizontal or vertical, which can be ascribed with the classical bit states of zero and one, respectively. But polarization can also be in a superposition of these two states, which means, in a way, it is both zero and one at the same time. Superposition lies at that heart of quantum information processing. Because the means to manipulate the polarization of photons are well-understood and easily available, optics is an ideal test-bed for investigating quantum effects and information. Quantum optics allowed the first realizations of novel effects such as teleportation, quantum key distribution and various other computation and communication techniques. IQC is a hub of cutting-edge research in quantum optics. The seminal proposal by Emanuel Knill, Raymond Laflamme and Gerald Milburn (known as the KLM proposal) allows universal and scalable optical quantum computing using only single photons, linear optics and measurement. Norbert Lütkenhaus has conducted leading research into entanglement verification, linear optic quantum logic operation and measurement implementation. The research group led by Kevin Resch focuses on fundamental experiments and implementations of quantum communication and algorithms, while researchers including Thomas Jennewein are working toward technologies that will allow for quantum communication through free space over great distances via satellite.

### **SPIN-BASED QUANTUM INFORMATION PROCESSING**

A natural early test-bed for ideas in quantum information processing made use of the manipulation of quantum states of individual nuclear magnetic moments (spins) in molecules suspended in solution. This so-called liquid-state nuclear magnetic resonance (NMR) was a natural first tool to probe the quantum world, since it borrows many ideas relying on quantum mechanics that were previously well-developed for biomedical imaging. Fundamental and important experiments continue to be carried out using this platform. In fact, a team of researchers led by IQC Director Raymond Laflamme and David Cory hold the current record for the highest number of well-characterized qubits harnessed in a single experiment (12). IQC's faculty includes several pioneers and leaders of NMR-based quantum computing, such as Laflamme, Deputy Director Michele Mosca, and professors Debbie Leung and Andrew Childs. Moreover, IQC professors Joseph Emerson and Jonathan Baugh have also made significant contributions to ideas in quantum information processing that were tested or executed using NMR quantum computation at IQC.

To reach the next stage of implementations for quantum information processing, many researchers are trying to find a platform that can be scaled up to an increasingly large number of qubits. In particular, Jonathan Baugh's research focuses on single electron spins confined to nanoscale structures, such as point defects, quantum wires, carbon nanotubes, or semiconductor quantum dots. This platform, which relies on nanoscale fabrication techniques developed in the semiconductor industry, has the potential for the creation of a system with many qubits, where the full power of quantum information processing might be realized.

### **NANOELECTRONICS-BASED QUANTUM INFORMATION PROCESSING**

Nanoelectronic systems such as quantum dots and superconducting circuits are good candidates for a practical quantum information processor, as they are based on the standard semiconductor technology for fabrication. Once we have a few working (above a given threshold), it should be possible to make many work together in a scalable technology. Since their first realization, in which only the slightest indication of coherent control was observed, errors in these systems have reduced to 1-2%. Two-qubit gates have been demonstrated, entanglement has been observed, and simple quantum algorithms have been implemented. IQC is in the initial phases of setting up two experimental labs in these fields: the Quantum Spintronics Laboratory and Superconducting Quantum Devices. IQC faculty members Adrian Lupascu and Frank Wilhelm are leaders in research with superconducting qubits. Jonathan Baugh's laboratory at IQC is centred around quantum dots in wires and nuclear polarization, while Hamed Majedi's laboratory research is focused on superconducting single-photon detectors.

# **STAKEHOLDERS**

## **INDUSTRY CANADA**

Industry Canada donated \$50 million to IQC to be allocated over a five-year period. In the 2009/2010 year, \$16.5 million was awarded with the following allotment: \$12.5 million for the construction of the Quantum-Nano Centre, \$1.0 million for equipment purchasing, \$1.1 million toward highly qualified personnel, \$0.6 million toward knowledge transfer and \$1.3 million for operations.

## **MIKE AND OPHELIA LAZARIDIS**

Mike and Ophelia Lazaridis have donated a total of \$101 million to IQC since inception. Just over four million dollars of their generous donation went toward the Waterloo Institute of Nanotechnology.

## **THE GOVERNMENT OF ONTARIO**

The Government of Ontario has granted \$50 million to the University of Waterloo to help strengthen Ontario's leading-edge research capacity. The Ontario Ministry of Research and Innovation granted IQC \$18 million.

## **THE UNIVERSITY OF WATERLOO**

The University of Waterloo has committed to supporting the salaries of IQC faculty.

## **CANADIAN FOUNDATION FOR INNOVATION**

CFI has contributed nearly \$24 million to IQC since inception.

## **NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL OF CANADA**

NSERC has committed over \$7.5 million to developing quantum information science and technology since the inception of IQC in 2002.

## **CANADA RESEARCH CHAIRS**

The Canada Research Chairs Secretariat Program supports IQC through faculty positions at UW that are jointly appointed by IQC and one of the departments in the Faculties of Science, Engineering or Mathematics. Current Research Chairs at IQC are: Raymond Laflamme, Michele Mosca and Debbie Leung.

## FUNDING AGREEMENT WITH INDUSTRY CANADA

The five-year grant from Industry Canada will enable the establishment of a new world-class research facility, which will support the government's science and technology strategy aimed at building a strong Canadian economy via knowledge and innovation. In the long term, Industry Canada expects four key outcomes as a result of this grant:

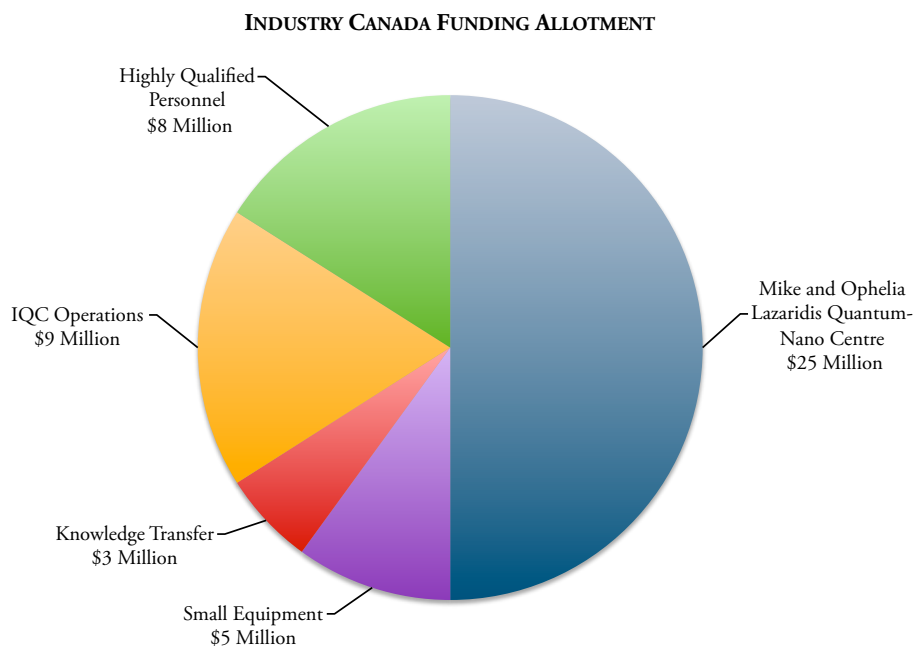
1. Increased knowledge in quantum information
2. New opportunities for students to learn and apply new knowledge
3. Canada branded as a place to conduct research in quantum technologies
4. Canada positioned to take advantage of economic and social benefits of research

This chart illustrates the distribution of Industry Canada funds over five years:

Fiscal Year	Funding Amount (\$ in Millions)
<b>2010</b>	<b>\$16.5</b>
2011	\$17.0
2012	\$5.0
2013	\$5.5
2014	\$6.0
<b>Total</b>	<b>\$50.0</b>

With the aim of supporting IQC in its pursuit of these expected results, Industry Canada has allotted \$25 million over two years to the construction of the new Mike and Ophelia Lazaridis Quantum-Nano Centre, \$5 million over five years for the purchase of small equipment and \$20 million over five years to the following four activities:

5. Recruiting and retaining highly qualified personnel
6. Transferring knowledge
7. Supporting administrative and technical staff members
8. Purchasing materials and supplies (other than small equipment)



## **BUDGET & FINANCIAL STATEMENTS (\$000s)**

### **2010 SPENDING AND BUDGET FOR THE NEXT FOUR YEARS**

	<b>2010</b>	<b>2011</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>TOTAL</b>
Building	12,615	12,385				25,000
Equipment	938	1,062	1,000	1,000	1,000	5,000
People & Operations	2,947	3,553	4,000	4,500	5,000	20,000
<b>TOTAL</b>	<b>16,500</b>	<b>17,000</b>	<b>5,000</b>	<b>5,500</b>	<b>6,000</b>	<b>50,000</b>



# **OBJECTIVES**

IQC has three fundamental objectives that will help to fulfill its mission of developing and advancing quantum information science and technology through the collaboration of computer scientists, engineers, mathematicians and physical scientists:

1. Establish Waterloo as a world-class centre of research in quantum technologies and their applications
2. Become a magnet for students and postdoctoral fellows in the field of quantum information
3. Establish IQC as the prime source of authoritative information, analysis and commentary on quantum information

For the purpose of the Industry Canada grant, these will be measured through the following more specific objectives:

1. Conduct research in quantum information
2. Recruit researchers
3. Collaborate with other researchers
4. Building facilities and laboratory support
5. Attract, educate and train highly qualified personnel
6. Disseminate knowledge
7. Develop and communicate the IQC brand
8. Administrative support

Below is a breakdown of each area including background information, specific activities, timeline and expected results.

## **1. CONDUCT RESEARCH IN QUANTUM INFORMATION**

### **BACKGROUND**

The institute's primary mandate is to conduct research in quantum information science at the highest international level. This goal has necessitated the ongoing recruitment of top faculty and students, the acquisition of cutting-edge equipment and resources, and the creation of a working environment that fosters scientific excellence. The continued expansion of the institute will allow researchers at IQC to explore new theoretical and experimental approaches to quantum information processing over the next year.

### **ACTIVITIES & TIMELINE**

- Leading-edge investigation of theoretical approaches to quantum information processing in order to:
  - Better understand the impact of quantum mechanics for information processing
  - Investigate new potential applications
- Develop approaches to quantum information using photonic, nuclear and electron spins, quantum dots, superconducting technologies and study the requirements needed to design earth to satellite quantum cryptography systems

### **EXPECTED RESULTS**

The research at IQC will produce new knowledge that will lead to publications and presentations at conferences. This knowledge will include a better understanding of quantum information processors and

laboratory demonstrations of their control, and the development of technologies based on these processors. Ultimately it will lead to new technologies and applications.

## **2. RECRUIT RESEARCHERS**

### **BACKGROUND**

The mission of IQC is to develop and harness quantum information science and technology at the highest international level through the collaboration of computer scientists, engineers, mathematicians and physicists. To this end, IQC must continue to build a team of theoretical and experimental researchers who are leaders in their respective disciplines. With such top researchers, IQC can achieve its other strategic objectives: becoming a magnet for students and postdoctoral researchers, and becoming the authoritative source of information, analysis and commentary about quantum information.

### **ACTIVITIES & TIMELINE**

- Recruit between up to three new faculty members
- Recruit between six to 10 new postdoctoral fellows
- Recruit 20 new graduate students
- Leverage conferences and other outreach forums as recruitment opportunities

### **EXPECTED RESULTS**

The ongoing recruitment of top-tier faculty to IQC will further enhance the institute's fundamental objective of pursuing quantum information research at the highest international level. Assembling a critical mass of theoretical and experimental researchers, exploring a broad range of approaches to quantum information processing, will establish IQC at the forefront of the field. This, in turn, will fuel the institute's objectives of being a magnet for top students and being the authoritative source for information and analysis on the field. Fulfilling all these objectives will put IQC, and therefore Canada, at the forefront of the international pursuit of quantum information technologies.

## **3. COLLABORATE WITH OTHER RESEARCHERS**

### **BACKGROUND**

The field of quantum information processing spans many disciplines — physics, chemistry, computer science, mathematics and others — and we expect that many breakthroughs will come from collaborations between researchers from a variety of fields. At IQC we are pursuing opportunities (joint grants, research projects, memoranda of understanding) to forge strong collaborative relationships with top scientists and researchers around the world.

### **ACTIVITIES & TIMELINE**

- IQC to be a catalyst to facilitate collaborations of quantum information scientists through networks such as QuantumWorks, Canadian Institute for Advanced Research (CIFAR) Quantum Information program and the Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Networks
- Researchers will attend international conferences on quantum information processing to build networks and connections
- Increased number of publications co-authored by IQC researchers and external collaborators
- Organize three conferences that involve multi-disciplinary participants
- Continue, enhance and increase visits to IQC by researchers from around the world

### **EXPECTED RESULTS**

Strategic collaborations with key researchers from across disciplines will enhance IQC's international reputation, draw highly qualified personnel to IQC, and lead to experimental and theoretical breakthroughs (for example, the QIP=PSPACE breakthrough achieved by IQC's John Watrous and

outside collaborators). By fostering such collaboration, IQC will become an world-class centre for research and development of quantum information technologies.

#### **4. BUILDING, FACILITIES AND LABORATORY SUPPORT**

##### **BACKGROUND**

IQC's mission is to develop and advance quantum information science and technology through collaboration of computer scientists, engineers, mathematicians and physical scientists. There are currently two construction projects underway that will help IQC achieve this goal. The Research Advancement Centre 2 (RAC2) will host some of the IQC's future projects and the Mike and Ophelia Lazaridis Quantum-Nano Centre (QNC) will become IQC's new headquarters. The QNC is located at the heart of the University of Waterloo's main campus. The centre will be home to a 20,000 sq. ft. fabrication and metrology lab as well as the Waterloo Institute for Nanotechnology.

##### **ACTIVITIES**

- Proceed with the construction of the Mike and Ophelia Lazaridis Quantum-Nano Center and ensure that the building is constructed per specifications, on time and on budget
- Establish a new 10,000 sq. ft. laboratory in the Research Advancement Centre 2 (RAC2) building with research focused on quantum sensors and actuators
- Prepare equipment and other resources for expansion into to the QNC
- Continue acquisition and maintenance of equipment for RAC1 laboratories

##### **TIMELINE**

- RAC2 will be completed June 2010
- QNC construction
  - The floor slabs on floors two to five were completed
  - The main structure of building was completed in March 2010
  - Currently, the exterior building envelope is approximately 20 per cent complete
  - The building will be watertight by August 2010
  - The majority of the mechanical and electrical work will be completed by April 2011
  - The building construction will be complete in July 2011

##### **EXPECTED RESULTS**

This activity will result in buildings and equipment that are installed and operational.

#### **5. ATTRACT, EDUCATE AND TRAIN HIGHLY QUALIFIED PERSONNEL**

##### **BACKGROUND**

While IQC possesses a critical mass of leading researchers in quantum information science, it is imperative for the future of the institute to recruit, educate and train the next generation of leaders in the field. The path toward the realization and commercialization of practical quantum information technologies will be forged by the next waves of student researchers. Seeking out those prospective students, recruiting them to IQC and providing them with the necessary resources and guidance is therefore critical to the long-term mission and vision of IQC.

##### **ACTIVITIES & TIMELINE**

- Roll-out the graduate program
- Establish an open house event for graduate students to attract prospective applicants
- Enhance prominence and content of graduate studies program on the IQC website (including background information, course materials, etc.)
- Attend at least four graduate fairs to connect with prospective students
- Field at least 120 applications to the UW/IQC graduate studies program (a 20 per cent increase over applications in 2009/2010)
- Host an information session for University of Waterloo students

## **EXPECTED RESULTS**

The establishment of a Graduate Program will be an important tool for IQC to be a magnet for students. The Graduate Student Open House will aid in the recruitment of top-tier students who may be weighing various options. Enhancing the content, accessibility and interactivity of the Graduate Studies section of the IQC website will aid in attracting the best students from around the world. These means of student-targeted outreach will lead to an increased number of applications to the graduate studies program, providing a larger pool of prospective applicants from which IQC can recruit the best.

## **6. DISSEMINATE KNOWLEDGE**

### **BACKGROUND**

Meetings, workshops, conferences and outreach activities are organized annually to complement the research that is happening at IQC. These events range from general interest lectures to highly specialized conferences. IQC is currently working on a website redesign project that will influence the outreach strategy and the dissemination of knowledge in the future.

### **ACTIVITIES & TIMELINE**

- Host five conferences at IQC with 3 distinct target audiences including researchers, undergraduate students and high school students
- Complete website redesign project and launch new web presence
- Compile a database of the publications by IQC researchers on RefBase<sup>2</sup>
- Increase external media coverage

### **EXPECTED RESULTS**

The increase in outreach and knowledge dissemination will help to achieve the strategic objective of establishing IQC as the authoritative source of information, analysis and commentary on quantum information. It will also help to promote IQC as a world-class centre of research in quantum technologies and their applications.

## **7. DEVELOP AND COMMUNICATE THE IQC BRAND**

### **BACKGROUND**

IQC's communications and outreach goals are guided by IQC's three strategic objectives, most directly to establish IQC as the authoritative source of information, analysis and commentary on quantum information. The Communications and Outreach Strategy encompasses: identifying key audiences, stakeholders and messages, developing tools and processes for communications, building relationships with outreach partners, and identifying the institute's unique culture to build the IQC brand.

### **ACTIVITIES & TIMELINE**

- Assemble the full communications and outreach team by August 2010
- Lay IQC branding groundwork, including market research, focus groups, interviews/surveys with stakeholders – beginning summer 2010
- Complete website redesign to increase IQC's web presence, interactivity and outreach scope
- Develop key messages and themes for IQC communications
- Targeted outreach to highlight IQC's scientific strengths and attract researchers to the institute
- Planning for IQC's 10<sup>th</sup> anniversary and the expansion into the new Quantum-Nano Centre

### **EXPECTED RESULTS**

The establishment of a full, five-member Communications and Outreach team will allow for the creation and execution of a long-term strategy that fulfills IQC's objective of becoming the authoritative source of analysis and insight on quantum information. The addition of an Associate Director of Communications & Outreach will allow the team to operate more strategically and autonomously. This in turn will lead to the development of communications strategies, outreach activities and a clear IQC brand that fully

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<sup>2</sup> A reference management software tool

conveys IQC's stature as the authoritative source of information, analysis and commentary on quantum information.

## **8. ADMINISTRATIVE SUPPORT**

### **BACKGROUND**

The fundamental function of IQC's administrative team is to provide researchers and students with the professional support needed to pursue leading-edge research in quantum information. To this end, it is necessary for the administrative team to have clearly delineated roles and responsibilities that fully support the scientific goals of the Institute. To support and sustain the many academic, research and outreach activities at IQC, it is necessary to develop and maintain best practices for financial standards, processes and documentation.

Information technology is integral to IQC's success and its support ranges from enabling administrative functions to supporting scientific research and online outreach. IQC's information technology strategy encompasses infrastructure, information/transaction management and stakeholder support.

### **ACTIVITIES & TIMELINE**

- Documenting and standardizing processes, jobs and back-ups in a rapidly expanding institute
- Planning for expansion into RAC2 and the QNC
- Establishing a grant life cycle process for standardizing and tracking sources of funding
- Developing desktop and other software/hardware tools and techniques
- Developing tools and processes for a new website

### **EXPECTED RESULTS**

The creation of standardized processes will create efficiency and repeatability for IQC's administration in the long-term. The clear establishment of roles and responsibilities will allow administrative personnel to better support the scientific activities at IQC. Establishing an efficient, standardized process for monitoring grant details (grant names, amounts, investigators, agencies) will allow greater efficiency in attaining and tracking funding sources. Refining and streamlining information technology processes for IQC researchers and staff will enable the highest quality work. Providing IQC personnel with the resources necessary for their roles and help reduce support demands and improve efficiency, allowing longer-term planning of IT strategies.

To review IQC's 2009 objectives see Appendix B.

## **RESEARCH RELATED RESULTS**

### **NEW GRANTS**

According to the University of Waterloo Office of Research:

In addition to Industry Canada's grant of \$16.5 million for this year, IQC received **75** grants between April 1, 2009 and March 31, 2010<sup>3</sup> totaling \$7,379,979 for a grand total of **\$23,879,979**.

During the period of April 1, 2008 and March 31, 2009, IQC received **76** grants totaling **\$5,017,117**.

### **COLLABORATIVE RESEARCH**

Collaborative research between peers typically results in the joint writing, submission and publication of a co-authored paper. IQC faculty members collaborated with 141 external researchers in the publication of 41 joint papers during 2009. Many more publications resulted from collaborations between researchers internally at IQC.

<b>41</b>	Published papers co-authored by IQC faculty and non-IQC researchers
<b>141</b>	Number of non-IQC co-authors on publications <sup>4</sup>
<b>6</b>	Grants shared between IQC faculty and non-IQC researchers
<b>46</b>	Number of non-IQC researchers sharing joint grants with IQC faculty
<b>61</b>	Institutes whose researchers have collaborated with IQC faculty

For a more detailed account of IQC's collaborative research see Appendix E.

### **MEMORANDA OF UNDERSTANDING**

IQC has signed four new agreements in the past year and has a total of six agreements to date.

National University of Singapore - Memorandum of Understanding (March, 2010)

International Business Machines (IBM) – Software License Agreement (January, 2010)

National Science Council of Taiwan - Statement of Understanding (December, 2009)

COM DEV – Non-Disclosure Agreement (September, 2009)

Indian Institute of Technology, Kanpur – Memorandum of Understanding (April, 2006)

National Institute of Informatics, Japan – Memorandum of Understanding (December, 2005)

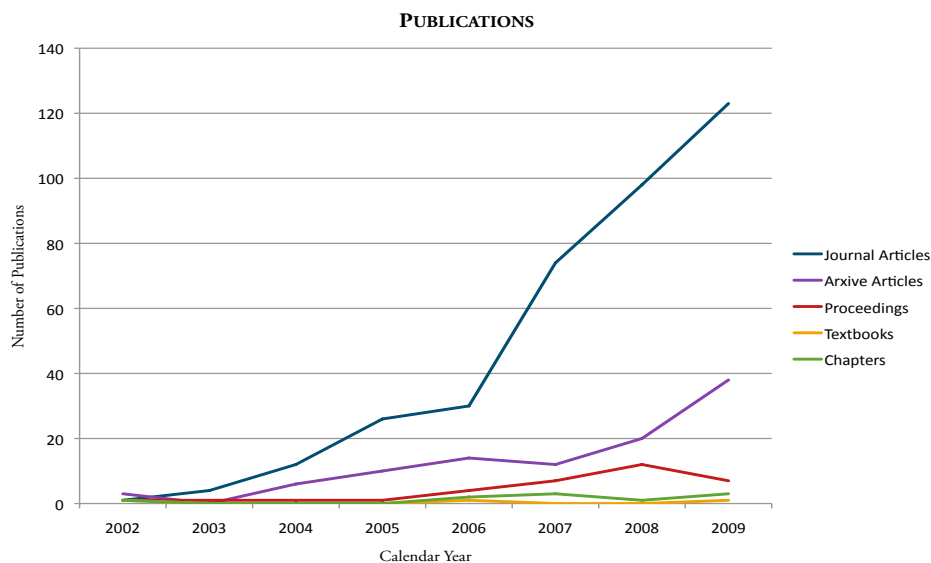
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<sup>3</sup> This information is based on the University of Waterloo Office of Research fiscal year and runs from April 1, 2009 to March 31, 2010

<sup>4</sup> Versus full-time IQC members, not including affiliate or associate members

## PUBLICATIONS

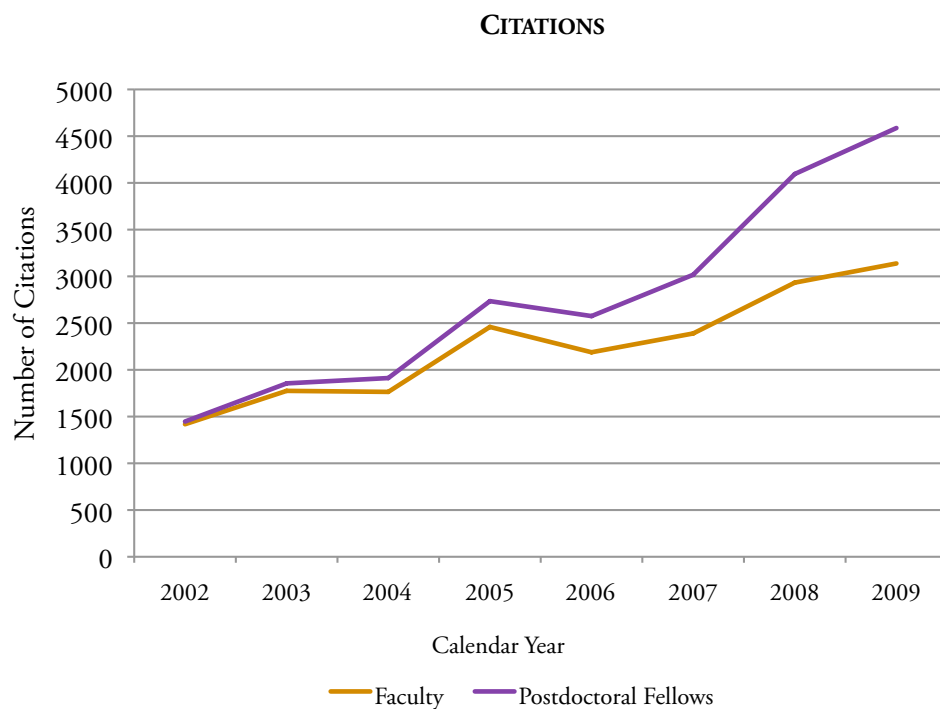
Below is a graph of the increases in journal articles, paper proceedings, textbooks, chapters and arxiv.org articles.



Calendar Year	Journal Articles	Arxiv.org Articles	Proceedings	Textbooks	Chapters
2002	1	3	1	1	1
2003	4	0	1	0	0
2004	12	6	1	0	0
2005	26	10	1	0	0
2006	30	14	4	1	2
2007	74	12	7	0	3
2008	98	20	12	0	1
2009	123	38	7	1	3

## **CITATIONS**

The chart below shows the increase of citations of IQC faculty and postdoctoral fellow publications<sup>5</sup>.



Calendar Year	Faculty	Postdoctoral Fellows
2002	1418	1447
2003	1775	1855
2004	1764	1912
2005	2459	2735
2006	2188	2575
2007	2389	3017
2008	2933	4095
2009	3138	4587

<sup>5</sup> This data is from the ISI Web of Knowledge only.



## NUMBER/TYPE OF RESEARCHERS AT IQC

IQC is home to 18 faculty members, 1 research assistant professor, 25 postdoctoral fellows, 63 graduate students, two graduate research assistants and 15 undergraduate research assistants.

Below is a graph showing the percentages of experimental and theoretical researchers in fiscal year 2010.

	Experimental	Theoretical
Faculty	7	11
Research Assistant Professor	0	1
Postdoctoral Fellows	9	16
Graduate Students	29	34
Long-term Visitors	4	6
Graduate Research Assistants	1	1
Undergraduate Research Assistants	9	6

## COLLABORATIVE GRADUATE PROGRAM IN QUANTUM INFORMATION

The Ontario Council for Graduate Studies approved the new collaborative graduate program in January of 2010. The program is accepting applications for September 2010. The University of Waterloo and IQC are working together to offer students a new interdisciplinary approach to graduate studies and an opportunity to earn an MMath, MSc, MASc or PhD degrees.

The program is offered in collaboration with:

- The Faculty of Mathematics
  - Department of Applied Mathematics
  - Department of Combinatorics and Optimization
  - David R. Cheriton School of Computer Science
- The Faculty of Science
  - Department of Chemistry
  - Department of Physics and Astronomy
- The Faculty of Engineering
  - Department of Electrical and Computer Engineering

The graduate program will expose students to a wide range of advanced research projects and courses on the foundations, applications and implementations of quantum information processing. One particularly special feature of the new graduate program is its scope and breadth, encompassing both experimental and theoretical aspects of quantum information. Students will be required to take two key courses: Quantum Information Processing, and Implementation of Quantum Information Processing, and will have the opportunity to take a wide range of other specialized courses in quantum information, ranging from Theory of Quantum Information to Quantum Algorithms to Nanoelectronics Implementations of Quantum Information Processing.

## **NEW COURSES**

The quantum information program is introducing the following courses (pending approval by the University of Waterloo Senate Graduate and Research Council) starting in the 2010-2011 academic year:

QIC710 Quantum Information Processing

- Cross-listed with AMATH 871, CS 667, C&O 681, PHYS 767

QIC750 Implementation of Quantum Information Processing

QIC845 Open Quantum Systems [every 2 years]

- Cross-listed with AMATH876 Open Quantum Systems

QIC823 Quantum Algorithms [every 2 years]

QIC820 Theory of Quantum Information [every 2 years]

- Cross-listed with CS766 Theory of Quantum Information

QIC885 Quantum Electronics and Photonics

- Jointly offered with ECE770-14 Quantum Electronics and Photonics

QIC880 Nanoelectronics for QIP [every 2 years]

QIC890 Topics in Quantum Information [lecture course]

Possible Topics Include:

Magnetic Resonance and Spin-based Quantum Information Processing

Quantum Communication Theory

Quantum Error Correction and Fault-Tolerance

Implementation of Quantum Communication

Applied Quantum Cryptography

Quantum Optics and Atomic Physics for QIP

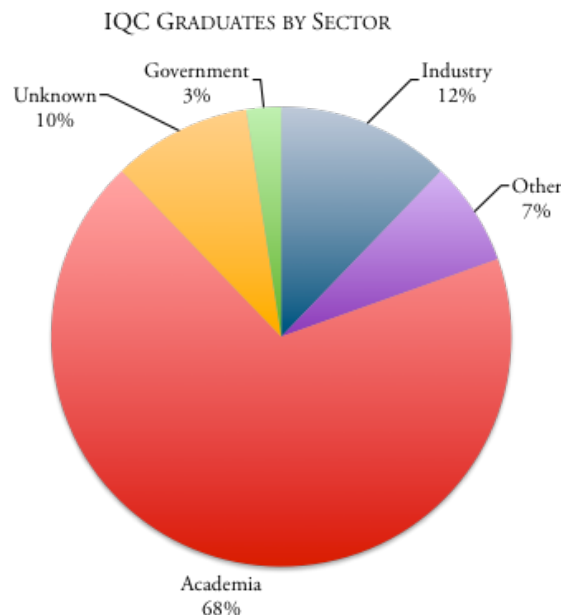
QIC895 Topics in Quantum Information [reading course]

## **PRACTICAL OPPORTUNITIES FOR GRADUATES**

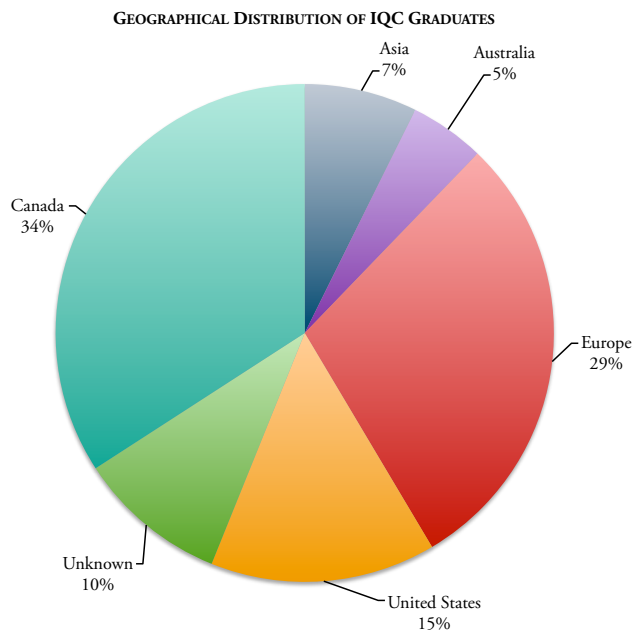
Along with the establishment of the new collaborative graduate studies program in quantum information comes the question of what type of practical opportunities graduates might when they complete their studies at IQC.

There are 41 graduates of the IQC graduate program to this date.

Below is the breakdown of the sectors in which IQC's past students are currently working.



Of the 41 IQC graduates to date, 14 have remained working in Canada. Nine of those have remained in academia, one entered government and four entered positions in industry. The grads working outside of Canada are currently in Asia, Australia, Europe and North America as illustrated below.



### **FACULTY AWARDS**

- Michele Mosca, “40 Under 40” award from *The Waterloo Region Record*, Feb 2010
- Raymond Laflamme, senior scientific advisor, and Joseph Emerson, scientific advisor and co-writer, “Prix Audace” at Pariscience Film Festival for *The Quantum Tamers*, Oct. 2009
- John Watrous, “STOC” prize for best paper 2010, QIP=PSPACE with Rahul Jain

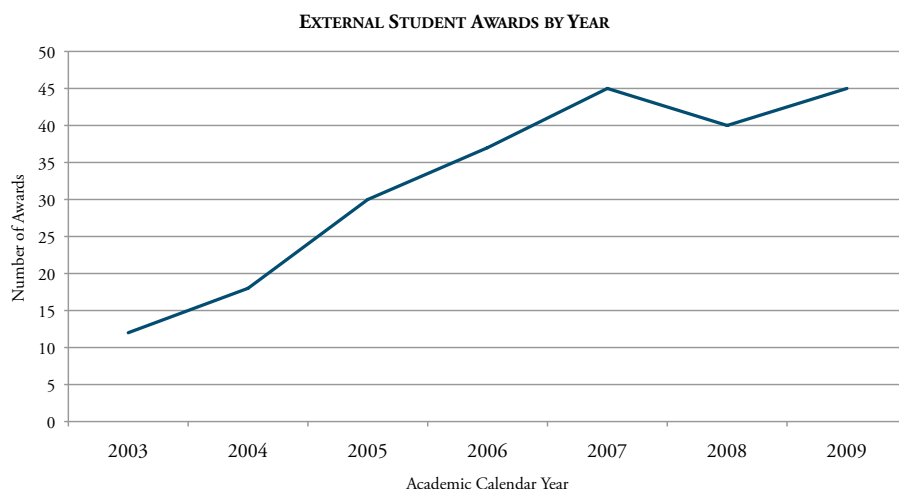
### **POSTDOCTORAL FELLOW AWARDS**

- Jay Gambetta, CIFAR Junior Fellow, June 2009
- Bill Coish, CIFAR Junior Fellow, March 2009
- Anne Broadbent, NSERC Doctoral Prize

### **STUDENT AWARDS**

#### **EXTERNAL**

Below is a graph depicting the increase in number of student awards since 2003. These results are shown on the academic year (September to August).



**DAVID R. CHERITON GRADUATE SCHOLARSHIP**

Sevag Gharibian	Sarvagya Upadhyay
Gus Gutoski	

**NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP - DOCTORAL**

Jonathan Lavoie	Magesan Easwar
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**NSERC ALEXANDER GRAHAM BELL CANADA GRADUATE SCHOLARSHIP - MASTERS**

Ben Criger	Pierre-Luc Dallaire-Demers
Evan Meyer-Scott	Deny Hamel
Robin Kothari	

**NSERC POSTGRADUATE SCHOLARSHIP - DOCTORAL**

Jamie Smith	Chris Erven
Christopher Ferrie	Jamie Sikora

**NSERC POSTGRADUATE SCHOLARSHIP - MASTER'S EXTENSION**

Deny Hamel	Gina Passante
Ryan Morris	Jamie Smith

**NSERC VANIER CANADA GRADUATE SCHOLARSHIP**

Gina Passante

**ONTARIO GRADUATE SCHOLARSHIP**

Thomas McConkey	Kurt Schreiter
Hamid Mohebbi	Brendan Osberg
Jamie Sikora	Cozmin Ududec

**ONTARIO GRADUATE SCHOLARSHIP IN SCIENCE AND TECHNOLOGY**

Felix Motzoi

**PRESIDENT'S GRADUATE SCHOLARSHIP**

Pierre-Luc Dallaire-Demers	Chris Erven
Christopher Ferrie	Thomas McConkey
Evan Meyer-Scott	Gina Passante
Hamid Mohebbi	Ryan Morris
Brendan Osberg	Jamie Smith
Cozmin Ududec	Ben Criger
Deny Hamel	Easwar Magesan
Robin Kothari	Jonathan Lavoie
Kurt Schreiter	Jamie Sikora

## **INTERNAL STUDENT AWARDS**

There are two internal scholarships available to IQC students: The Mike and Ophelia Lazaridis Fellowship and the Gordon Bell IQC Achievement Award.

In the history of IQC, there have been:

- 16 recipients of the IQC Achievement Award (formerly the Bell Family Research Fund Award)
  - Five in FY 2010
- 10 recipients of the Mike and Ophelia Lazaridis Fellowship
  - Two in FY 2010

## **IQC STUDENTS FROM TOP UNDERGRADUATE SCHOOLS IN CANADA**

The Times Higher Education World University Rankings judge educational institutions based on peer review, academic polls, teacher-to-student ratios, internationalization rate and number of research citations.

This year, 40 of IQC's 63 graduate students studied at one or more of these top-ranked graduate or undergraduate institutions.

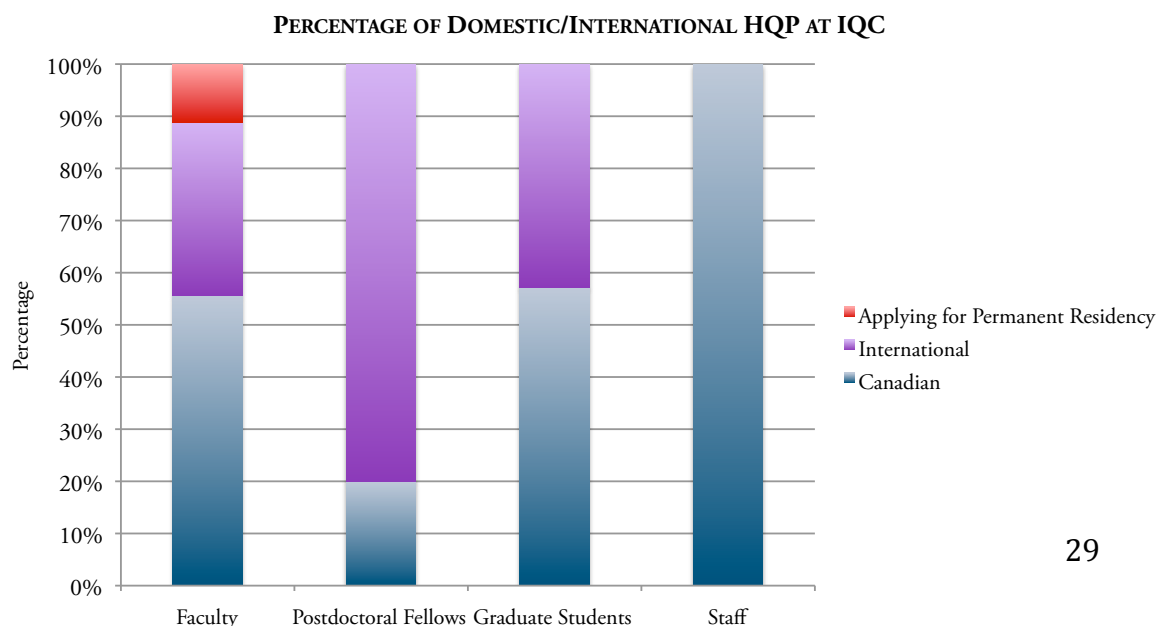
For more information on the Times Higher Education World University Ranking see Appendix H.

## **STUDENTS WITH A HIGH GRADE POINT AVERAGE**

61 per cent of students have a GPA score of 90 per cent or higher

85 per cent of students have a GPA score of 85 per cent or higher

## **DOMESTIC VS. INTERNATIONAL HQP AT IQC**



	Canadian	Applying for Permanent Residency	International
Faculty	10	2	6
Postdoctoral Fellows	5	0	20
Graduate Students	36	0	27
Staff	17	0	0

### **NUMBER OF WORKSHOPS HELD**

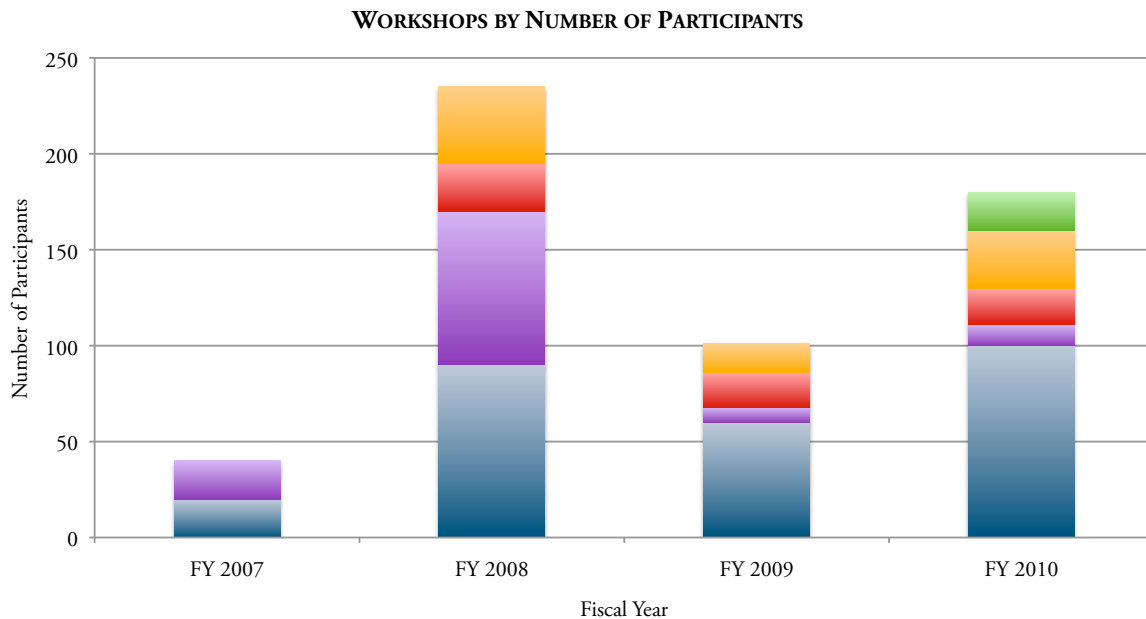
Over the past year, IQC hosted five conferences:

1. The Fourth Workshop on Theory of Quantum Computation, Communication and Cryptography, May 11 – 13, 2009, 100 participants
  - Objective: To foster interaction between researchers and allow for sharing of problems and recent discoveries.
2. USEQIP: Undergraduate School on Experimental Quantum Information Processing, June 1 – 12, 2009, 11 participants
  - Objective: To introduce undergraduate students to the field of quantum information processing.
3. QCSYS: Quantum Cryptography School for Young Students, July 27 – 31, 2009, 19 participants
  - Objective: To introduce secondary school students to the field of quantum information processing.
4. Mathematics in Experimental Quantum Information Processing Workshop, August 10 – 15, 2009. 30 participants
  - Objective: To bring together leading experts in mathematical approaches to quantum information processing
5. UW/MIT Spintronics Meeting, September 19 – September 22, 2009, 20 participants
  - Objective: To exchange information and collaborate on research in spin-based quantum information processing

Below is a depiction of the number of participants at conferences hosted by IQC each year. In each year a different colour represents a distinct workshop<sup>6</sup>.

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<sup>6</sup> In the 2007 – 2008 year, two large rotating conferences with 80 and 90 participants visited IQC. This accounts for the jump and subsequent fall in number of participants at the conferences in 2008 – 2009



### **NUMBER OF PRESENTATIONS**

IQC faculty members presented at a total of 58 events in the 2009 calendar year.

A full list of the presentations is available in Appendix I. This list only includes presentations away from IQC headquarters.

### **APPLICATIONS TO IQC**

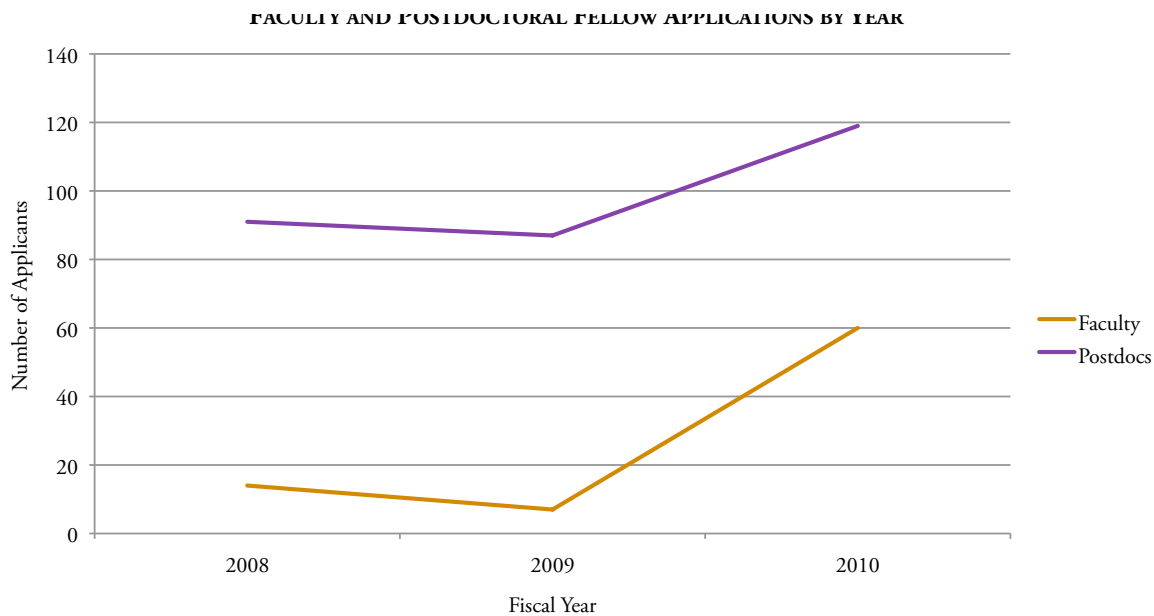
#### **FACULTY & POSTDOCTORAL FELLOWS**

IQC received a total of 119 applications to postdoctoral fellow positions within the last fiscal year.

There were 60 applications to faculty positions within the fiscal last year<sup>7</sup>.

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<sup>7</sup> Note there was a University-wide hiring freeze during fiscal 2009



Fiscal Year	Faculty Applications	Postdoctoral Fellow Applications
2008	14	91
2009	7	87
2010	60	119

## **STUDENTS**

There were 104 applications to UW/IQC indicating interest in quantum computing from May 1, 2009 to April 30, 2010.

## **SPINOFFS, DISCLOSURES & PATENTS**

Dr. Thomas Jennewein, in collaboration with Raymond Laflamme and Steve MacDonald, is currently exploring the possibility of establishing a company aiming to commercialize devices suitable for measuring entangled photon sources, implementing quantum cryptography systems and experiments involving photon correlation with quantum dots. Hopefully, these devices will be made available to research laboratories worldwide.



# INFRASTRUCTURE RELATED RESULTS

## THE MIKE AND OPHELIA LAZARIDIS QUANTUM-NANO CENTRE

The new Mike and Ophelia Lazaridis Quantum-Nano Centre will allow faculty and students to pursue quantum information research at the highest level. Shared with the Waterloo Institute of Nanotechnology, the building will foster cross-disciplinary collaboration in its many common areas, lounges and meeting rooms. IQC's headquarters will allow the institute to continue its aggressive growth, with an expected doubling of personnel over the next several years to 30 faculty, 50 postdoctoral fellows and 125 students.

Designers of the building were guided by three principles:

1. It must be functional, i.e. meet the highest scientific standards, including stringent vibration and temperature, humidity and low electromagnetic radiation standards
2. It must encourage interaction and collaboration between researchers and students
3. It should serve as a magnet for top scientists to Waterloo



## CONSTRUCTION UPDATE

The structure of the QNC building was completed in March 2010. The exterior building envelope is currently approximately 20 per cent complete.

The building will be watertight by August 2010.



QNC Construction site: April 27, 2010

By April 30, 2011, the majority of the mechanical and electrical work will be completed. The construction of the building should be complete in July 2011.

Since the construction has not yet been completed, there is currently no equipment in place at the QNC.

The QNC project remains within the approved budget and is being constructed per University of Waterloo specifications

IQC's estimated expenditures to April 30, 2010 are \$37 million.

All funding provided by Industry Canada for the 2010 fiscal year with regards to the QNC construction has been expended.

The contracted completion date for the QNC facility is July 2011. The University of Waterloo is working with the general contractor to ensure this date is met.

The construction of the QNC has created 128 jobs related to the Industry Canada grant<sup>8</sup>.

## **FACILITIES FOR RESEARCH AND TRAINING**

### **RESEARCH ADVANCEMENT CENTRE 1**

IQC is currently headquartered in the Research Advancement Centre (RAC1) in the University of Waterloo's Research and Technology Park. The 70,000-sq. ft., three-storey building houses seven experimental labs and a cleanroom/fabrication facility equipped with fume hoods, spin coaters and an e-beam lithography system. RAC1 is home to most of IQC's faculty, postdoctoral fellows, students and staff. With the rapid growth of the institute, lab space is at a premium and IQC will be expanding into portions of RAC2.

### **RESEARCH ADVANCEMENT CENTRE 2**

Construction in RAC2 will be completed by June 2010. RAC2 is a twin building directly adjacent to RAC1. The University of Waterloo will lease the first floor of the building and use a portion of the rest to accommodate IQC researchers and their laboratory infrastructure.

IQC aims to retain lab space in RAC1 and RAC2 once the Mike and Ophelia Lazaridis Quantum-Nano Centre is completed.

Industry Canada provided \$1 million toward the purchase of small equipment. The purchases made with the money from Industry Canada helped IQC to create, improve and add value to its facilities to foster leading-edge quantum information research and training.

### **LABORATORIES & SMALL EQUIPMENT**

IQC's new 1,650 sq. ft. cleanroom in RAC1 was designed to suit the needs of semiconductor fabrication equipment, which is instrumental to research being led by IQC researchers Jonathan Baugh and Adrian Lupascu. Dr. Lupascu's research requires Helium-3 gas, which has increased in price from \$400 USD to \$2,000 USD per litre. Because Dr. Lupascu's original grant did not account for this price increase, Industry Canada funds were used to offset the prices of 36 litres of Helium-3, allowing Dr. Lupascu's work to continue. Upgrades to facilities and equipment in RAC1 also included the purchasing of cleanroom apparatus, software and hardware, a spectrometer, a laser network analyzer and coverage of maintenance costs. The allocation of this funding allows IQC researchers to be competitive among their global peers in the field of quantum information science.

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<sup>8</sup> If \$100,000 equals one job

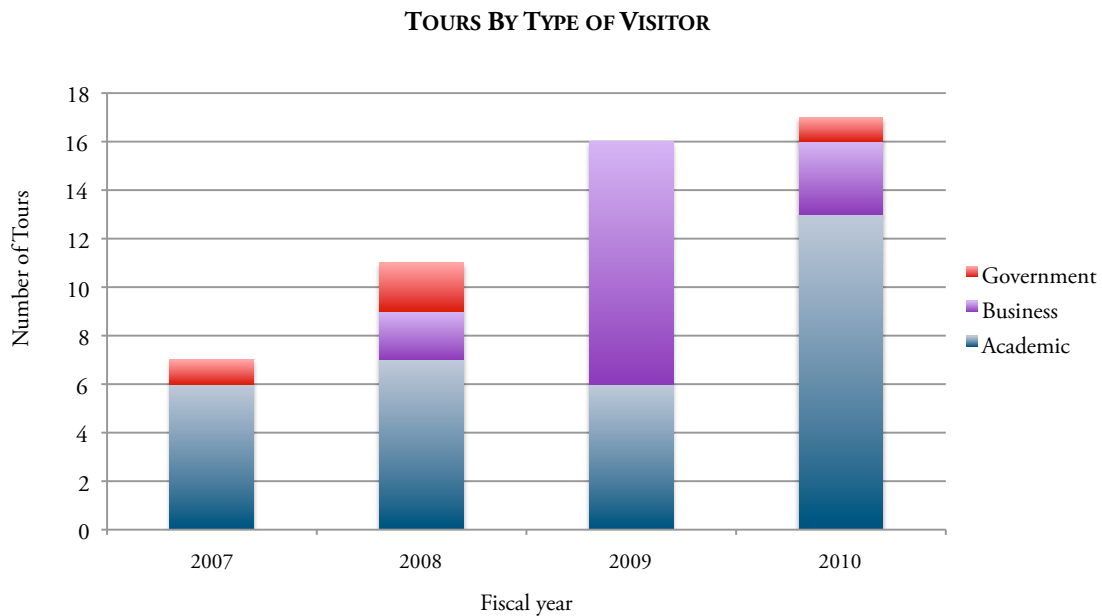
## **FACILITY TOURS**

### **RAC1 TOURS**

IQC offers group tours of the RAC1 facility at varying levels of technical complexity. Researchers at the institute often help guide tours for high school students, business people, government officials and community members.

Tour groups are made up of at least 10 participants. Smaller groups or single guests are tracked in as visitors on page 39.

Below is a tally of the group tours at IQC over the past four years. The type of visitor is also indicated.



Fiscal Year	Academic Tours	Business Tours	Government Tours
2007	6	0	1
2008	7	2	2
2009	6	10	0
2010	13	3	1

### **QNC TOURS**

The construction site at the QNC is not yet open for public tours. However, the Premier of Ontario, Dalton McGuinty, visited the QNC construction site on August 24, 2009. IQC's Board of Directors visited the QNC site during the October 2009 Board Meeting.

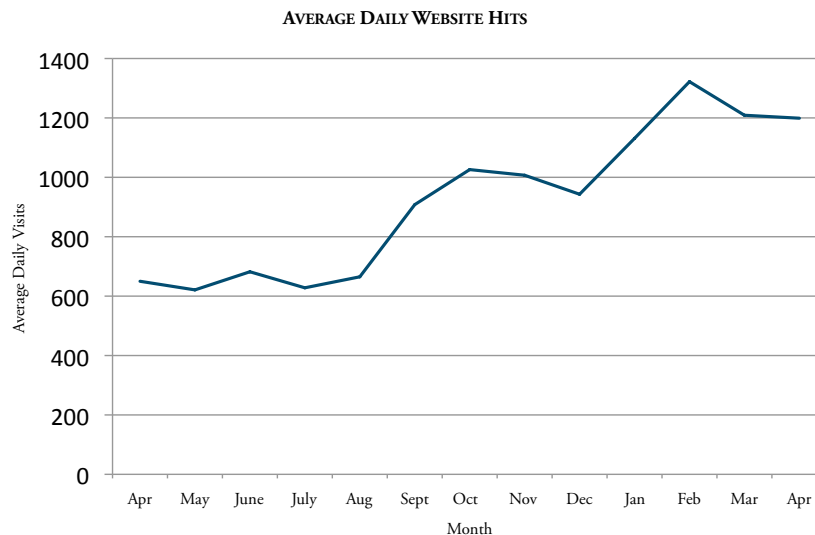
# OUTREACH AND KNOWLEDGE DISSEMINATION RESULTS

## WEBSITE

The IQC website is home to the key information about the institute including the mission, strategic objectives, historical facts, information about what motivates IQC's research, sponsor and donor acknowledgements and information about the construction of the Quantum-Nano Centre. The website also houses a full directory of all IQC members, a calendar of events, seminars, conferences, colloquia, etc. Information about the graduate program, the EU exchange program, the visitor program and outreach activities is also available.

The current website does not include a great deal of information about the specific research groups or projects happening at the institute. However, with the implementation of a new web platform in early summer of 2010, this information will become readily available.

The IQC website was last updated on March 24, 2010. The usual update cycle for news items is bi-weekly. Depending on their nature, news items remain visible on the homepage of iqc.ca for three to four weeks. The update cycle for the more static items is annually or bi-annually.



## **OUTREACH ACTIVITIES**

In addition to the five conferences already mentioned, IQC has coordinated or participated in nine specific outreach activities in the past year.

1. Tony Leggett Lecture Series
  - June 4 to July 2, 2009
  - 40 participants per talk
2. Gregory Chaitin Lecture
  - September 23, 2009
  - 60 participants
3. University of Waterloo Science Open House Day
  - September 24, 2009
4. Quantum to Cosmos
  - October 15 – 25, 2009
  - Participation by Laflamme, Mosca and Broadbent
5. IQC Open House and Public Lecture
  - October 17, 2009
  - 125 participants
6. Quantum Dance
  - October 17, 2009
  - 75 participants
7. TEDxWaterloo (Laflamme)
  - February 24, 2010
8. Perimeter Institute Public Lecture (Emerson)
  - March 3, 2010
9. Graduate Fairs
  - University of Waterloo Graduate Fair
    - September 29, 2009
  - Canadian Undergraduate Physics Conference Graduate Fair
    - September 4, 2009
  - McGill Graduate and Professional Schools Fair
    - November 4, 2009
  - Atlantic University Physics and Astronomy Conference Graduate Fair
    - February 5 – 7, 2010

In addition, IQC has increased its web presence on Twitter and Facebook in hopes of reaching a wider audience. Within the last year, IQC has set up several social media accounts:

The @QuantumIQC twitter account has 195 followers.

The IQC Facebook account has 197 fans.

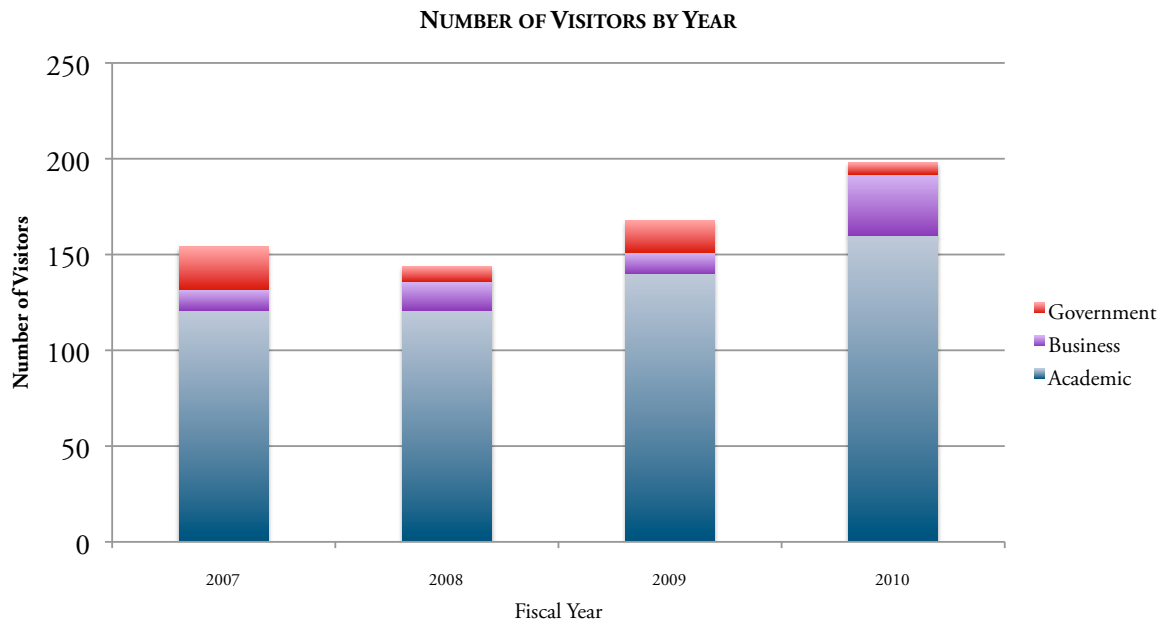
QuantumIQC YouTube Channel has two videos uploaded with a total of 103 views.

## **VISITORS**

IQC often invites scholars, government officials and business people to visit the people or facility. Within the last year, IQC welcomed:

- 148 academic visitors
- 15 business visitors
- 6 government visitors

Below is a depiction of the number of visitors over the past four years including a breakdown of the type of visitor.



Fiscal Year	Academic Visitors	Business Visitors	Government Visitors
2007	121	11	22
2008	121	15	8
2009	140	11	17
2010	160	32	6

## **PRESS RELEASES & MEDIA COVERAGE**

In the 2010 fiscal year, IQC was featured in 33 articles or stories put out by third-party publications.

The University of Waterloo published 17 articles about IQC during the year and IQC published 36 articles or press releases.

## **BRANDING PLAN & COMMUNICATIONS ROADMAP**

The Communications and Outreach Roadmap is guided by IQC's three strategic objectives, most directly Objective 3: "To become an authoritative source of information, analysis and commentary on the state of quantum information processing and provide the essential knowledge for Canada's industry to be ahead of the international community."

### **KEY COMPONENTS OF THE ROADMAP**

- Website re-launch and management, for improved web presence, authority and accessibility
- Media relations: print/TV/online coverage of IQC people and science. Making IQC the authoritative source for info and insight on quantum computing
- Branding: crafting the outward face and perception of IQC
- Outreach events (TEDx Waterloo, Doors Open, student camps)
- Scientific outreach: targeted at prospective faculty, students, postdoctoral fellows (spearheaded by incoming Manager of Scientific Outreach)
- Targeted outreach to stakeholders, funders, taxpayers, partners
- Outreach targeted specifically at prospective students, reaching them through best channels

### **THE TEAM**

Since Nov. 2009, three new Communications & Outreach personnel have been added to IQC's team: two Communications Specialists and a Manager of Scientific Outreach (to begin in May 2010). All will work closely with the Events Coordinator.

The hiring process is now underway for an Associate Director of Communications & Outreach. This role will be filled by Spring 2010.

### **NEXT STEPS**

- Communications/Outreach work with consultant
  - Currently seeking RFPs from three firms to choose best option
- Branding strategy with consultant, including:
  - Market research
  - Surveys of key audiences
  - Interviews with key stakeholders
  - Current brand review and assessment
  - Building a communications strategy
  - IQC communications audit/analysis

### **UPCOMING OUTREACH OPPORTUNITIES**

Doors Open, media coverage of IQC personnel, summer camps (USEQIP, QCSYS), OCE Conference, grant announcements, UW Innovation & Emerging Technologies festival, grad program, new faculty (CERC), move to Quantum-Nano Centre, etc.

## RISKS ASSESSMENT & MITIGATION STRATEGIES

		LIKELIHOOD		
		Low	Med	High
IMPACT	High	6	8	9
	Med	3	5	7
	Low	1	2	4

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
1) IQC may not be able to attract high quality researchers	High	Medium	8	The market for world-class researchers is highly competitive, and IQC is still building brand awareness. However, researchers are the cornerstone on which institutional reputation is built	<ul style="list-style-type: none"> <li>Pursue recruits from a wide breadth of areas of research</li> <li>Offer competitive job offers/package.</li> <li>Adequately promote world class facilities/equipment</li> </ul>



Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
2) Key staff may defect from IQC	High	Medium	8	IQC's research and recruitment efforts are largely the responsibility of a few key individuals. These individuals would be difficult to replace	<ul style="list-style-type: none"> <li>Diversify the nature of staff members' work</li> <li>Provide a challenging work environment</li> <li>Ensure adequate technical and administrative support</li> <li>Ensure world-class facilities and equipment</li> <li>Provide a stimulating environment</li> <li>Provide attractive benefits and employee/spousal programs.</li> </ul>
3) Transformational technologies may render current research less relevant	High	Low	6	If IQC research is rendered less relevant, HQPs and data seekers will go elsewhere	<ul style="list-style-type: none"> <li>Ensure a wide breadth of research to investigate (this would differentiate IQC from its competitors)</li> <li>Continue applications for research funds to support leading edge equipment</li> </ul>
4) Graduate program may not be approved or may suffer delays	Medium	Low	3	Delays may hinder IQC's recruitment efforts	<ul style="list-style-type: none"> <li>Ensure high-quality graduate program application</li> <li>Resubmit application if rejected</li> </ul>
5) IQC may not be able to recruit enough HQPs	High	Low	6	Many international HQPs come from potentially politically unstable countries (top three are Iran, China, India)	<ul style="list-style-type: none"> <li>Promote IQC sufficiently</li> <li>Ensure excellent research</li> <li>Diversify markets/ countries from which students are recruited</li> </ul>

<b>Risk Factor</b>	<b>Impact Score</b>	<b>Likelihood Score</b>	<b>Risk Rating</b>	<b>Explanation of Score</b>	<b>Mitigation Measures</b>
6) Lack of financial information (regarding endowment) impedes long term planning	High	Low	6	Sustainability/ source of funds (other than IC) is largely unknown	<ul style="list-style-type: none"> <li>• Prepare a 10-year financial plan for ongoing operations</li> </ul>
7) Operating constraints limit IQC's efforts to brand itself	High	Low	6	Operating constraints include limited resources (including staff), degree of flexibility	<ul style="list-style-type: none"> <li>• Recruit the right people/talent/skills</li> <li>• Develop and deliver a branding project plan</li> <li>• Foster close working relationships with appropriate units within the university</li> </ul>
8) Construction costs may exceed budget	Low	Medium	2	The IC grant amount is fixed. University has committed to compensate for shortfall.	N/A
9) Construction schedule may be delayed	Medium	Low	3	Outcomes would be delayed, but not changed	N/A

# APPENDIX

## APPENDIX A: IQC MEMBER LIST

### FACULTY

- |                     |                        |                   |
|---------------------|------------------------|-------------------|
| 1. Andris Ambainis  | 7. Raymond Laflamme    | 13. Ashwin Nayak  |
| 2. Jonathan Baugh   | 8. Debbie Leung        | 14. Ben Reichardt |
| 3. Andrew Childs    | 9. Adrian Lupascu      | 15. Kevin Resch   |
| 4. Richard Cleve    | 10. Norbert Lütkenhaus | 16. John Watrous  |
| 5. Joseph Emerson   | 11. Hamed Majedi       | 17. Gregor Weihs  |
| 6. Thomas Jennewein | 12. Michele Mosca      | 18. Frank Wilhelm |

### RESEARCH ASSISTANT PROFESSOR

1. Dmitri Maslov

### POSTDOCTORAL FELLOWS

- |                   |                     |                   |
|-------------------|---------------------|-------------------|
| 1. Gorjan Alagic  | 9. Lawrence         | 17. Mohsen Rasavi |
| 2. Dominic Berry  | Ioannou             | 18. Colm Ryan     |
| 3. Anne Broadbent | 10. Tsuyoshi Ito    | 19. Simone        |
| 4. Bill Coish     | 11. Rainer          | Severini          |
| 5. Alexander De   | Kaltenbaek          | 20. Urbasi Sinha  |
| Souza             | 12. Xiongfeng Ma    | 21. Yipu Song     |
| 6. Jay Gambetta   | 13. Will Matthews   | 22. Tzu-Chieh Wei |
| 7. Gus Gutoski    | 14. Seth Merkel     | 23. Zhizhong Yan  |
| 8. Hannes Huebel  | 15. Marco Piani     | 24. Bei Zeng      |
|                   | 16. Robert Prevedel | 25. Jingfu Zhang  |

### GRADUATE STUDENTS

- |                           |                           |                           |
|---------------------------|---------------------------|---------------------------|
| 1. Jeyran Amirloo         | 16. MirMojtaba Gharibi    | 32. Laura Mancinska       |
| 2. Normand Beaudry        | 17. Sevag Gharibian       | 33. Iman Marvian Mashhad  |
| 3. Devon Biggerstaff      | 18. Peter Groszkowski     | 34. Thomas McConkey       |
| 4. Jean-Philippe Bourgoin | 19. Deny Hamel            | 35. Matthew McKague       |
| 5. Jeremy Chamilliard     | 20. Tyler Holdon          | 36. Evan Meyer-Scott      |
| 6. Alessandro Cosentino   | 21. Rolf Horn             | 37. Hamid Mohebbi         |
| 7. Ben Criger             | 22. Stacey Jeffery        | 38. Ryan Morris           |
| 8. Pierre-Luc Dallaire-   | 23. Mohsen Keshavarz      | 39. Felix Motzoi          |
| Demers                    | 24. Botan Khani           | 40. Osama Moussa          |
| 9. Chunqing Deng          | 25. Milad Khoshnegar      | 41. Varun Narasimhachar   |
| 10. Amin Eftekharian      | 26. Nathan Killoran       | 42. Christian Oppenlander |
| 11. Chris Erven           | 27. Robin Kothari         | 43. Jean-Luc Orgiazzi     |
| 12. Agnes Ferenczi        | 28. Jonathan Lavoie       | 44. Brendan Osberg        |
| 13. Chris Ferrie          | 29. Nicholas LeCompte     | 45. Yingkai Ouyang        |
| 14. Jennifer Fung         | 30. Chandrashekar Madaiah | 46. Maris Ozols           |
| 15. Behnood Ghamsari      | 31. Easwar Magesan        | 47. Adam Paetznick        |

48. Gina Passante  
49. David Pitkanen  
50. Farzad Qassemi  
51. Ansis Romanis  
52. Bill Rosgen  
53. Amir Jafari Salim

54. Kurt Schreiter  
55. Cheng Shen  
56. Lana Sheridan  
57. Jamie Sikora  
58. Jamie Smith  
59. Jason T. Soo Hoo

60. Cozmin Ududec  
61. Savagya Upadhyay  
62. Rui Xian  
63. Mike Zhang

#### **STAFF**

1. Colin Bell  
2. Matthew Cooper  
3. Andrew Dale  
4. Monica Dey  
5. Michael Ditty  
6. Brian Goddard  
7. Jasmine Graham

8. Colin Hunter  
9. Laurie Kitchen  
10. Lorna Kropf  
11. Kimberly  
Simmermaker  
12. Vito Logiudice  
13. Steve MacDonald

14. Mary Lyn Payerl  
15. Suzette Pearson  
16. Wendy Reibel  
17. Marta  
Szepietowski

#### **UNDERGRADUATE RESEARCH ASSISTANTS**

1. Ruben Romero  
Alvarez  
2. Nick Coish  
3. Amira Eltony  
4. Dorian Gangloff  
5. Chantal  
Hutchinson

6. David Luong  
7. Allison  
MacDonald  
8. Ian McMullan  
9. Maxim Mitchell  
10. James Mracek  
11. Yudai Nakagawa

12. Daniel Park  
13. Ranmal Perera  
14. Thiru  
Sivakumaran  
15. Lu Yang

#### **GRADUATE RESEARCH ASSISTANTS**

1. Haig Atikian  
2. Ziaodi Wu

## **APPENDIX B: IQC'S 2009 OBJECTIVES**

The following originally appeared on IQC's 2009 grant proposal to Industry Canada. These objectives have since been updated with the help of Goss Gilroy Management Consultants and Industry Canada to form new objectives set out in section 2.2 on page 18. As a recap, the 2009 objectives appear below:

### **RESEARCH**

- Research will focus on three related paths:
  - Algorithms & Protocols (how to control and use quantum information processors)
  - Building blocks that make proof-of-principle demonstration of quantum information processing
  - Proof-of-principle experiments of quantum technologies
- Hiring: up to three additional faculty, six to 10 postdoctoral fellows, 20 students
- Write more than 100 research papers, organize three workshops/conferences, give more than 100 presentations/talks, host 50 research seminars
- Purchase equipment and outfit laboratories including the nanofabrication facility

### **GRADUATE PROGRAM AND TEACHING**

- Make IQC a magnet for the best undergraduate and graduate students and postdoctoral fellows in quantum information science and widely disseminate their results
  - Implement a collaborative graduate program in quantum information at the University of Waterloo to foster the next generation of quantum information scientists

### **OUTREACH**

- IQC will engage in outreach activities that will help with recruitment of graduate students and postdoctoral fellows
- Outreach to include:
  - 4<sup>th</sup> Workshop on Theory of Quantum Computation, Communication and Cryptography, Undergraduate School on Experimental Quantum Information Processing, Quantum Cryptography School for Young Students, Fields Institute Workshop (Mathematics in Experimental Quantum Information Processing), Annual Tony Leggett Lecture Series
- Communications to include building a team that will create a roadmap and budget for IQC key messages, tools and branding strategies

### **IQC BUILDING**

- Ensure building is constructed per specifications, on time and on budget
- Forming of ground floor slab, 2<sup>nd</sup> to 5<sup>th</sup> floor slabs, superstructure, and building envelope completion

### **FINANCE**

- Document funding requirements for completion of the building, to equip the facility and support IQC's strategic objectives
- Prepare a 10-year financial plan circuit

## **APPENDIX C: IQC GOVERNANCE**

Typically, a university-based institute would be based in a department within a faculty. However, due to the interdisciplinary nature of quantum computing, an innovative approach to governance was required.

IQC's faculty members are appointed in six departments:

- Combinatorics and Optimization
- Computer Science
- Applied Math
- Physics
- Chemistry
- Electrical and Computer Engineering

These departments span three faculties:

- Faculty of Mathematics
- Faculty of Science
- Faculty of Engineering

Other governing bodies that contribute to shaping the strategic direction of IQC include the institute's Board of Directors, the Executive Committee and the Scientific Advisory Committee.

### **BOARD OF DIRECTORS**

IQC's Board of Directors is made up of internationally recognized leaders from academia, business and government. The Board provides strategic advice on all aspects of management including finances, planning, commercialization and outreach.

Douglas Barber, Distinguished Professor-in-Residence, McMaster University  
Tom Brzustowski, RBC Professor, Telfer School of Management, Chair, IQC Board of Directors  
Paul Corkum, University of Ottawa and National Research Council  
George Dixon, Vice-president, University Research, University of Waterloo  
Cosimo Fiorenza, Vice-president and General Counsel, Infinite Potential Group  
David Fransen, Consul General, Canadian Consulate General in Los Angeles  
Peter Hackett, Executive Professor, School of Business at the University of Alberta & Fellow,  
National Institute for Nanotechnology  
Raymond Laflamme, Director, Institute for Quantum Computing  
Mike Lazaridis, President and Co-Chief Executive Officer, Research in Motion  
Steve MacDonald, Chief Operating Officer, Institute for Quantum Computing  
Michele Mosca, Deputy Director, Institute for Quantum Computing  
Peter Nicholson, Retired President, Council of Canadian Academies  
William R. Pulleyblank, Professor of Operations Research, United States Military  
Academic, West Point &

### **EXECUTIVE COMMITTEE**

IQC's Executive Committee is chaired by the Vice-president of Research at the University of Waterloo and is made up of the Deans of Mathematics, Science and Engineering and IQC's senior management team.

Thomas F. Coleman, Dean, Faculty of Mathematics, University of Waterloo  
George Dixon, Vice-president, Chair, University Research, University of Waterloo  
Raymond Laflamme, Director, Institute for Quantum Computing  
Steve MacDonald, Chief Operating Officer, Institute for Quantum Computing  
Terry McMahon, Dean, Faculty of Science, University of Waterloo  
Michele Mosca, Deputy Director, Institute for Quantum Computing  
Adel S. Sedra, Dean, Faculty of Engineering, University of Waterloo

#### **SCIENTIFIC ADVISORY COMMITTEE**

IQC's Scientific Advisory Committee is made up of leading international scientists. It provides scientific guidance on recruitment, research projects and the overall research plan.

Harry Buhrman, Professor, Centrum voor Wiskunde en Informatica  
Anthony J. Leggett, Professor, University of Illinois at Urbana-Champaign  
Gerard Milburn, Professor, University of Queensland  
Umesh Vazirani, Professor, University of California, Berkley  
Anton Zeilinger, Professor, University of Vienna  
Wojciech Hubert Zurek, Laboratory Fellow, Los Alamos National Laboratory

#### **MIKE AND OPHELIA LAZARIDIS QUANTUM-NANO CENTRE COMMITTEE**

The Mike and Ophelia Lazaridis Quantum-Nano Centre is presently being constructed to host the increasing number of IQC researchers. This committee meets semi-annually to stay involved with the oversight of construction of the QNC. The committee reviews progress reports on the building's status, manages change related to alterations in design (including cost and timeline implications) and other issues.

Arthur Carty, Executive Director, Waterloo Institute for Nanotechnology  
Feridun Hamdullapur, Provost, University of Waterloo, Chair  
Dennis Huber, Vice-president, Administration and Finance, University of Waterloo  
Raymond Laflamme, Director, Institute for Quantum Computing  
Terry McMahon, Dean, Faculty of Science, University of Waterloo  
Adel S. Sedra, Dean, Faculty of Engineering, University of Waterloo

## APPENDIX D: FISCAL 2010 GRANTS

<b>Sponsor</b>	
CBIE: Canadian Bureau for International Education (1)	10,000
CFI Operating: Canada Foundation for Innovation Operating (2)	17,320
CFI-IOF Operating: Canada Foundation for Innovation- Infrastructure Operating Fund (1)	155,100
CFI-LEF: Canada Foundation for Innovation - Leading Edge Fund (1)	1,394,714
Canada Foundation for Innovation- Leaders Opportunity Fund (1)	164,000
CIFAR: Canadian Institute for Advanced Research (10)	320,000
CRC-NSERC: Communications Research Centre- Natural Sciences and Engineering Research Council of Canada (4)	450,000
CSE: Communications Security Establishment Canada (2)	47,550
ERA: Early Researcher Award (4)	117,179
HRDC: Human Resource Development Council (1)	61,760
Institute of Photonic Science (1)	20,965
MITACS: Mathematics of Information Technology and Complex Systems (5)	53,000
MITACS – Industry (2)	45,715
MRI-PDF Award: Ministry of Research and Innovation - Post-Doctoral Fellowship (1)	25,000
NSERC: Natural Sciences and Engineering Research Council of Canada (15)	519,194
NSERC Strategic: Natural Sciences and Engineering Research Council of Canada, Strategic Project Grants Program (1)	253,000
OCE: Ontario Centres of Excellence (3)	452,400
ORF-RI: Ontario Research Fund- Research Infrastructure (2)	2,408,462
Premier's Discovery: Premier's Discovery Award (Ministry of Research and Innovation) (1)	125,000
Quantum Works (9)	305,500
University of Toronto (1)	18,000
University of Wisconsin (2)	213,220
US Army Reserve Office (1)	162,900
Vice-President Academic (4)	40,000
	<b>7,379,979</b>
Industry Canada	16,500,000
	<b>\$23,879,979</b>



## APPENDIX E: COLLABORATIONS

Collaborative Publication Title	Co-authors	# of external collaborators	Publication
Building a spin quantum bit register using semiconductor nanowires	J. Baugh, J. S. Fung, J. Mrazek and R. R. Lapierre,	2	Nanotechnology
The quantum query complexity of certification	A. Ambainis, A. M. Childs, F. Le Gall, and S. Tani	1	Quantum Information and Computation, arXiv:0903.1291.
Efficient discrete-time simulations of continuous-time quantum query algorithms	R. Cleve, D. Gottesman, M. Mosca, R. Somma, and D. Yonge-Mallo	2	ACM Symp. on Theory of Computing (STOC 2009)
Entanglement-resistant two-prover interactive proof systems and non-adaptive private information retrieval systems	R. Cleve, D. Gavinsky, and R. Jain	2	Quantum Information and Computation, 9: 648–656, 2009.
Exact and approximate unitary 2-designs and their application to fidelity estimation	C. Dankert, R. Cleve, J. Emerson, and E. Livine	2	Physical Review A, 80: 012304 (6 pages), 2009
Three Slit Experiments and the Structure of Quantum Theory	C. Ududec, H. Barnum, J. Emerson	1	submitted to Foundations of Physics (2009)
Anti-symmetrization reveals hidden entanglement	A. Fedrizzi, T. Herbst, M. Aspelmeyer, M. Barbieri, T. Jennewein and A. Zeilinger	5	Institute of Physics Select (2009)
The security of practical quantum key distribution	V. Scarani, H. Bechmann-Pasquinucci, N.J. Cerf, M. Dusek, N. Lütkenhaus, M. Peev	3	Rev. Mod. Phys. Vol 81, p. 1301 (2009)
Unconditional security of the Bennett 1992 quantum key-distribution scheme with strong reference pulse,	K. Tamaki, N. Lütkenhaus, M. Koashi, J. Batuwantudawe	2	Phys. Rev. A Vol 80, 032302 (2009)
Topological optimization of quantum key distribution networks	R. Alleaume, F. Roueff, E. Diamanti, N. Lütkenhaus	3	Topological optimization of quantum key distribution networks

The SECOQC quantum key distribution network in Vienna	M. Peev, C. Pacher, R. Alléaume, C. Barreiro, J. Bouda, W. Boxleitner, T. Debuisschert, E. Diamanti, M. Dianati, J. F. Dynes, S. Fasel, S. Fossier, M. Fürst, J.-D. Gautier, O. Gay, N. Gisin, P. Grangier, A. Happe, Y. Hasani, M. Hentschel, H. Hübel, G. Humer, T. Länger, M. Legré, R. Lieger, J. Lodewyck, T. Lorünser, N. Lütkenhaus, A. Marhold, T. Matyus, O. Maurhart, L. Monat, S. Nauerth, J.-B. Page, A. Poppe, E. Querasser, G. Ribordy, S. Robyr, L. Salvail, A. W. Sharpe, A. J. Shields, D. Stucki, M. Suda, C. Tamas, T. Themel, R. T. Thew, Y. Thoma, A. Treiber, P. Trinkler, R. Tualle-Brouri, F. Vannel, N. Walenta, H. Weier, H. Weinfurter, I. Wimberger, Z.	1 <sup>9</sup>	New J. Phys, Vol 11 075001 (2009)
Symmetric extension in two-way quantum key distribution	L. Yuan, H. Zbinden and A. Zeilinger	2	Phys. Rev. A 79, 042329 (2009)
Asymptotic security of binary modulated continuous-variable quantum key distribution under collective attack	G. O. Myhr, J. M. Renes, Andrew C. Doherty and N. Lütkenhaus	2	Phys. Rev. A 79, 012307 (2009)
Can Closed Timelike Curves or Nonlinear Quantum Mechanics Improve Quantum State Discrimination or Help Solve Hard Problems?	Y.-B. Zhao, M. Heid, J. Rigas and N. Lütkenhaus	3	Phys. Rev. Lett. 103:170502, 2009
Improving zero-error classical communication with entanglement	Charles H. Bennett, Debbie Leung, Graeme Smith, John A. Smolin	1	arXiv:0911.5300 new accepted for 2010 conf.
Adaptive versus non-adaptive strategies for quantum channel discrimination	Toby S. Cubitt, Debbie Leung, William Matthews, Andreas Winter	2	arXiv:0909.0256
Non-Poissonian statistics from Poissonian light sources with application to passive decoy state quantum key distribution	Aram W. Harrow, Avinatan Hassidim, Debbie W. Leung, John Watrous	1	Opt. Lett. Vol 34, Iss. 20, pp 3238-3240 (2009)

<sup>9</sup> This is a research network based in Vienna with 54 members

Detector decoy quantum key distribution	M. Curty, T. Moroder, X. Ma, N. Lütkenhaus	1	New J. Phys, 11, 045008 (2009)
Microtraps for neutral atoms using superconducting structures in the critical state	A. Lupaşcu, A. Emmert , M. Brune , G. Nogues , M. Rosticher , F.-R. Ladan, J.-P. Maneval , and J.-C. Villégier	7	accepted for publication in the Proceedings of the IEEE Toronto International Conference - Science and Technology for Humanity (2009)
High-resolution spatial mapping of superconducting NbN wire using single-electron detection	M. Rosticher , F.-R. Ladan, J.-P. Maneval, T. Zijlstra, T. M. Klapwijk, S. N. Dorenbos, V. Zwiller, A. Lupaşcu, and G. Nogues	8	submitted (to ?)
Measurement of the trapping lifetime close to a cold metallic surface on a cryogenic atom-chip	A. Emmert, A. Lupaşcu, M. Brune , J.-M. Raimond, S. Haroche, and G. Nogues	5	Physical Review A, 80, 061604(R) (2009)
One- and two-photon spectroscopy of a flux qubit coupled to a microscopic defect	A. Lupaşcu, P. Bertet, E.F.C. Driessen, C.J.P.M. Harmans, and J.E. Mooij	4	Phys. Rev. B 72, 172506 (2009).
Effect of vortices on the spin-flip lifetime of atoms in superconducting atom-chips	G. Nogues, C. Roux, T. Nirrengarten, A. Lupaşcu, A. Emmert, M. Brune , J.-M. Raimond, S. Haroche B. Plaçais, and J.-J. Greffet	9	Europhysics Letters 87, 13002 (2009).
Recognizing well-parenthesized expressions in the streaming model	Frédéric Magniez, Claire Mathieu, and Ashwin Nayak	2	." Submitted to the 42nd Annual ACM Symposium on Theory of Computing, 2009
On parallel composition of zero-knowledge proofs with black-box quantum simulators	R. Jain, A. Kolla, G. Midrijanis, B. Reichardt	3	Quantum Information and Computation, 9:513-532, 2009. (IF:3.379, 5IF:2.959)
Quantum trajectory equation for multiple qubits in circuit QED: Generating entanglement by measurement	Hutchison, Chantal L.; Gambetta, J. M.; Blais, Alexandre; Wilhelm, F. K.	1	CANADIAN JOURNAL OF PHYSICS

Upper bounds for the secure key rate of decoy state quantum key distribution	M. Curty, T. Moroder, X. Ma, H.-K. Lo, N. Lütkenhaus;	2	Phys. Rev. A 79, 032335 (2009).
Two-message quantum interactive proofs are in PSPACE	R. Jain, S. Upadhyay, and J. Watrous.	1	Proceedings of the 50th Annual IEEE Symposium on Foundations of Computer Science (FOCS), pages 534–543, 2009.
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Adaptive versus non-adaptive strategies for quantum channel discrimination	Harrow, A. Hassidim, D. Leung, and J. Watrous	2	Submitted to Physical Review A in 2009. 11 pages.
Improving high-T <sub>c</sub> dc-SQUID performance by junction asymmetry (2008)	Urbasi Sinha, Aninda Sinha, Frank K. Wilhelm	1	Supercond. Sci. Technol. 22 (2009) 055002
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## APPENDIX G: STUDENT AWARDS

### EXTERNAL

David R. Cheriton Graduate Scholarship	Sevag Gharibian Sarvagya Upadhyay Gus Gutoski
NSERC Alexander Graham Bell Canada Graduate Scholarship - Doctoral	Jonathan Lavoie Magesan Easwar
NSERC Alexander Graham Bell Canada Graduate Scholarship - Masters	Ben Criger Pierre-Luc Dallaire-Demers Evan Meyer-Scott Deny Hamel Robin Kothari
NSERC Postgraduate Scholarship - Doctoral	Jamie Smith Chris Erven Christopher Ferrie Jamie Sikora
NSERC Postgraduate Scholarship - Master's Extension	Deny Hamel Gina Passante Ryan Morris Jamie Smith
NSERC Vanier Canada Graduate Scholarship	Gina Passante
Ontario Graduate Scholarship	Thomas McConkey Kurt Schreiter Hamid Mohebbi Brendan Osberg Jamie Sikora Cozmin Ududec
Ontario Graduate Scholarship in Science and Technology	Felix Motzoi

President's Graduate Scholarship	Pierre-Luc Dallaire-Demers Chris Erven Christopher Ferrie Thomas McConkey Evan Meyer-Scott Gina Passante Hamid Mohebbi Ryan Morris Brendan Osberg Jamie Smith Cozmin Ududec Ben Criger Deny Hamel Easwar Magesan Robin Kothari Jonathan Lavoie Kurt Schreiter Jamie Sikora
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# INTERNAL

Gordon Bell IQC Achievement Award	Bill Rosgen	May 09 to Aug 09
	Pierre-Luc Dallaire-Demers	Sept 09 to Dec 09
	Matthew McKague	Jan10 to Apr 10
	Evan Meyer-Scott	Sept 09 to Dec 09
	Jean-Luc Orgiazzi	Jan 10-Apr 10
The Mike and Ophelia Lazaridis Fellowship	Amin olah Eftekharian	Sept 09-Aug 10
	Ansis Rosmanis	Jan 10-Dec 10

## APPENDIX H: SCHOOLS FROM FINANCIAL TIMES

The Times Higher Education World University Rankings judge educational institutions based on peer review, academic polls, teacher-to-student ratios, internationalization rate and number of research citations.

Students currently at IQC come from the following highly ranked institutions:

California Institute of Technology	Queens University
Dartmouth College	Tufts University
École Normale Supérieure	University of Alberta
Indian Institute of Technology, Bombay	University of Basel
Massachusetts Institute of Technology	University of Calgary
McMaster University	University of Cambridge
Nanjing University	University of Oxford
Peking University	University of Toronto
	University of Waterloo

## APPENDIX I: PRESENTATIONS

This list does not include faculty presentations at IQC

### Jonathan Baugh

“Building spin-qubit registers using nanowires,” Dalhousie University, 7/2009

“An approach to building scalable solid-state spin qubit registers,” University of Guelph, Physics Department Colloquium, 3/2009

### Andrew Childs

“Universal computation by quantum walk,” 12th Workshop on Quantum Information Processing, SantaFe, 1/2009

“The relationship between continuous- and discrete-time quantum walk,” 11th Annual Southwest Quantum Information and Technology Workshop, Seattle 2/2009

“The relationship between continuous- and discrete-time quantum walk,” Toronto Ontario, QuantumWorks 4th Annual General Meeting, 6/2009

“The relationship between continuous- and discrete-time quantum walk,” Los Alamos National Lab, 9/2009

“The quantum query complexity of implementing black-box unitary transformations,” Massachusetts Institute of Technology, 10/2009

Quantum property testing for sparse graphs, University of Waterloo, Tutte Seminar, 12/2009

### Richard Cleve

“Quantum entanglement and notions of mathematical proof,” Montréal, Centre de recherches mathématiques, 2/2009

“Efficient discrete-time simulations of continuous-time quantum query algorithms,” Montréal, Université de Montréal, 2/2009

Reporting talk, to report on activities of the ARO-funded Centre for Quantum Algorithms (Waterloo/Calgary/Guelph), Minneapolis, Quantum Computing & Quantum Algorithms Program Review, 8/2009

**Joseph Emerson**

“Is your quantum processor better than the Jones' quantum processor?” INTRIQ workshop, Quebec, 10/ 2009

3rd Workshop on Quantum Chaos: Theory and Applications, Buenos Aires, 12/2009 (invited talk - cancelled due to family illness)

**Thomas Jennewein**

“Quantum cryptography history: 1984 - 2009,” Vienna, ECOC Conference Workshop, 9/2009

“Quantum information processing and communication with photons,” Fields Institute, Toronto Conference on Quantum Information and Quantum Control 8/2009

“Space-QUEST: quantum entanglement in space experiments,” Toronto, Quantum Works Progress Meeting, 6/2009

“Optical quantum computing: status and the route to scalability,” Innsbruck Austria, SFB conference 1/2009

**Raymond Laflamme**

Invited guest and speaker IBM, Markham, 10/ 2009

Fields Institute, 8/2009

Invited guest and speaker Canadian Quantum Information Student Conference  
Fields Institute 8/2009

Invited speaker X border workshop, Experimental Quantum Error Correction,  
University of Ottawa, 5/2009

Roundtable speaker Science Day at the Public Policy Forum on 5/2009

“A leap into a strange world,” CIFAR Thirst of knowledge series, 5/ 2009

Invited speaker Workshop on Quantum Information Science organized by the  
Office of Science and Technology in the US Vienna, Virginia, 24th of April  
2009

Conference dinner talk ITAC Board of Governor dinner, Kitchener, 4/2009

“Benchmarking quantum information processing devices,” Cortina d’Ampezzo, Italy, Scala  
Annual meeting, 2/2009

Discussion Leader Gordon Conference on quantum Lectures on NMR quantum  
information processing, at the 2nd Quantum Information School, Paraty, Brazil, 9/2009

**Norbert Lütkenhaus**

“Quantum communications realized II,” San Jose California, SPIE International Symposium on Integrated  
Optoelectronic Devices, 1/2009

“Verschränkung als benchmark in der quanten-kommunikation,” Erlangen Germany, University of Erlangen, 2/2009

"Squashing models for optical measurements in quantum communication," Tokyo, IQC-NII Meeting, 2/2009

“Quantum key distribution,” Vienna, 4/2009

“Quantum cryptography and computing: theory and implementation,” Poland, University of Gdansk, National Quantum Information Centre of Gdańsk. 9/2009

### **Debbie Leung**

“Classical and quantum information assurance –foundations and practice,” Schloss Dagstuhl, Germany, 7/2009

“Open problems in adaptive versus non-adaptive strategies for quantum channel discrimination,” UCSB, USA, Kavli Institute for Theoretical Physics, 9/2009

“Information, quantum information, and quantum information theory comment,” UCSB, USA, Kavli Institute for Theoretical Physics, 10/2009

“Entanglement can increase the zero error classical capacity of a classical channel,” Caltech, 11/2009

“Continuity of quantum channel capacities,” MIT, 4/2009

“Myths concerning adaptive strategies for quantum/classical channel discrimination,” Perimeter Institute, 6/2009

“Continuity of quantum channel capacities,” Toronto, Fields Institute, 8/2009

### **Adrian Lupascu**

“Mapping of the quantum efficiency of a superconducting single electron” Toronto, IEEE TIC-STH-SS, 9/2009

“Quantum non-demolition measurement of a superconducting qubit,” Sherbrooke, University of Sherbrooke, 7/2009

“Towards the preparation and trapping of single Rydberg atoms on an atom-chip,” Alton, CIFAR meeting, 5/2009

“Manipulation of trapped atoms on cryogenic atom chips,” Charlottesville, DAMOP APS meeting, 5/ 2009

“One- and two-photon spectroscopy of a flux qubit coupled to a microscopic defect,” Pittsburgh, APS March meeting, 3/2009

### **Hamed Majedi**

“Quantum optical detection in superconducting nanowire structure”, Kingston, Queens University, 10/2009

“Superconducting nanowire single photon detector: from theory to optoelectronic characterization”, Montreal, Polytechnique Montreal, 4/2009

### **Michele Mosca**

Classical and Quantum Information Assurance Foundations and Practice, Dagstuhl Seminar 09311, July 2009.

International Seminar on Quantum Networking, IMDEA Networks (Inst. Madrileño de Estudios Avanzados), Madrid, Spain, June 2009.

PCTS-MITRE Quantum Computation Seminar Series, Princeton University, 29 April 2009 “Discrete-Time Simulations of Continuous-Time Quantum Query Algorithms

“Quantum Information and its application to cryptography”, Calgary Institute for Quantum Information Science (IQIS) seminar, April 2009.

“Cryptography in a Quantum World”, Centre for Information Security and Cryptography (CISaC), Distinguished Lecture Series, April 2009.

### **Ashwin Nayak**



“Fault-tolerant quantum communication with constant overhead,” Piscataway, NJ, DIMACS seminar on Theoretical Computer Science, 9/2009

“Fault-tolerant quantum communication with constant overhead,” Cambridge, MA, MIT, 10/2009

“Fault-tolerant quantum communication with constant overhead,” Princeton, NJ, NEC Labs America, 12/2009

### **Ben Reichardt**

“Semi-definite programs for span programs,” UC Berkeley, 4/2009

“Semi-definite programs for span programs,” Waterloo, Perimeter Institute, 3/2009

“Quantum algorithms based on span programs: the general adversary bound is nearly tight for quantum query complexity,” University of New Mexico Physics & Astronomy seminar 4/2009

“Quantum algorithms based on span programs: The general adversary bound is nearly tight for quantum query complexity,” Caledon, CIFAR, Quantum Information Processing Meeting, 5/2009

“Span programs and quantum algorithms,” Santa Barbara, CA, Kavli Institute for Theoretical Physics, 10/2009

“Span programs and quantum query complexity: The general adversary bound is nearly tight for every boolean function,” Atlanta, GA, IEEE Symp. on Foundations of Computer Science, 10/2009

“Span programs and quantum query algorithms,” Princeton, NJ, Institute for Advanced Study, 9/2009

“Faster quantum algorithm for evaluating game trees,” California Institute of Technology, 11/2009

“Span programs and quantum query algorithms,” Malibu, CA, HRL Laboratories, 12/2009

### **Kevin Resch**

“Optical implementations of quantum information,” University of Waterloo, Canada 3/2009

“Quantum optics lectures and laboratory experiments,” University of Waterloo, Canada USEQIP Conference, 6/2009

“Chirped-pulse interferometry: ‘quantum’ interference with classical light,” Montreal, Canada McGill University, 3/2009

### **John Watrous**

“Quantum games.” Vienna, Virginia, Workshop on Quantum Information Science, 4/2009

“Semidefinite programs for completely bounded norms,” Toronto, Fields Institute, 7/2009

“Quantum computational complexity.” Toronto, Fields Institute, Canadian Quantum Information Summer School 8/2009

“QIP = PSPACE.” University of Waterloo, Cheriton Research Symposium, 9/2009

“QIP = PSPACE.” Princeton University, Center for Computational Intractability, 11/2009

### **Frank Wilhelm**

“This talk will change your view of physics,” Tuktoyaktuk, Canada, 97<sup>th</sup> International Fizix Conference, 2009

“Optimal control of imperfect qubits,” Santa Barbara, KITP program on quantum information science, 11/2009

“Digital quantum amplifiers,” Bad Honnef, Germany, 445<sup>th</sup> WE-Heraeus Seminar, 11/2009

“Transient current and noise in double quantum dots,” Wroclaw, Poland, Canada-Poland-Japan symposium on Nanotechnology, 10/2009

“Optimal control of open quantum systems,” Toronto, Canada, CQIQC III, 8/2009)

“Optimal control of imperfect qubits,” Herrsching, Germany, Quantum information processing in the solid state III, 7/2009

“Optimal control of imperfect qubits,” Goteborg, Sweden, Nobel Symposium on quantum bits for quantum computing, 5/2009

“Optimal control of open quantum systems, Santa Barbara, USA, KITP workshop on optimal control of light and matter, 5/2009

“Quantum microwave cavities: Nonclassical states and hybrid systems,” Whistler, Canada, CIFAR Nanoelectronics meeting, 5/2009

“Noise from a trapped Josephson bifurcation amplifier,” Pittsburgh, USA, APS March meeting, 3/2009

“Optimal control of imperfect qubits,” Riverside, USA, University of California, Electrical Engineering Seminar, 12/2009

“Quantum nanoelectronics,” Germany, Juelich Research Center 11/2009

“Superconducting qubits,” Saarbruecken, Germany, Saarland University, 11/2009

“Optimal control of imperfect qubits,” Germany, Karlsruhe Institute of Technology, Condensed Matter Theory Seminar, 11/2009

“Optimal control of imperfect qubits,” Madison, USA, University of Wisconsin, 9/2009

“Superconducting qubits,” Edmonton, Canada, University of Alberta, 9/2009

## APPENDIX J: IQC PRESS RELEASES

01-May-09	Prestigious award goes to PhD student
04-May-09	Taking a spin around the block
13-May	TCQ 2009 Underway
03-Jun-09	Sir Anthony Leggett Lecture Series
08-Jun-09	Canada Excellence Research Chair
17-Jun-09	Spotlight on quantum cryptography
19-Jun-09	New CIFAR Inductee
17-Jul-09	What great philanthropy can do
07-Aug-09	Fields Institute workshop begins next week
19-Aug-09	QIP = PSPACE
24-Aug-09	IQC faculty member wins Early Researcher Award
15-Sep-09	IQC welcomes new minds for fall term
16-Sep-09	Dr. Gregory Chaitin at IQC
23-Sep-09	IQC faculty member shares in US government grant
03-Oct-09	Public event: open house and panel discussion
21-Oct-09	Quantum Tamers captures prize in Paris
25-Nov-09	IQC featured in Nature
07-Jan-10	Quantum Grad program set for fall 2010
08-Jan-10	IQC researchers solve difficult classical problem with one quantum bit
27-Jan-10	Quantum grad program set for fall 2010
09-Feb-10	IQC faculty receive grant for collaborative research
11-Feb-10	The Quantum Tamers returns to TV
12-Feb-10	Researchers probe time travel as computing tool
24-Feb-10	Michele Mosca named among 40 Under 40
26-Feb-10	IQC director wows crowd at TEDxWaterloo
22-Feb-10	Joseph Emerson public lecture
04-Mar-10	IQC researchers investigate boson problems
09-Mar-10	International deal signed for quantum collaboration
15-Mar-10	IQC director featured in Motivated Magazine
22-Mar-10	Nature article examines quantum computing possibilities
24-Mar-10	Raymond Laflamme's TEDxWaterloo talk online
07-Apr-10	The Quantum Tamers to be screened in Ottawa
19-Apr-10	IQC researcher welcomes readers to quantum country
19-Apr-10	IQC deputy director named CIFAR Fellow
22-Apr-10	\$139K grant awarded to IQC researcher
03-May-10	Still time to sign up for QCSYS 2010

## APPENDIX K: MEDIA COVERAGE

### THIRD PARTY MEDIA COVERAGE

Date	Title	Publication
05-Jun-09	Lazaridis quantum gift tops \$101M	Waterloo Region Record

05-Jun-09	RIM co-CEO, wife, donate \$25 million to quantum research	Canadian Press
05-Jun-09	Another donation from Mike Lazaridis	570 News
05-Jun-09	Mike and Ophelia Lazaridis donations top \$101M	Exchange Magazine
17-Jul-09	Waterloo research park growing	Waterloo Region Record
25-Aug-09	High-tech center excites McGuinty	Waterloo Region Record
23-Sep-09	Quantum device group sharing in multi-institutional grant	azonano.com
28-Sep-09	Math guru sees miracle in Waterloo's intellectual culture	Waterloo Region Record
10-Oct-09	Harper government marks major investments in leading-edge research infrastructure	Marketwire
19-Oct-09	A quantum leap in film	Waterloo Region Record
Fall 2009	Are we the next big nano-hub	Tech Next
25-Nov-09	Quantum Potential	Nature
26-Nov-09	Bad news for time travelers	Nature Physics
09-Dec-09	Canada Revolutionizing ICT	Nikkei Business Daily
15-Dec-09	Group provides support for spouses of PhD students	Waterloo Region Record
08-Jan-10	Physicists solve difficult classical problem with one quantum bit	Nature Physics
26-Jan-10	Quantum computing	The Manitoban
29-Jan-10	The Next Frontier: Quantum Computing	The Globe and mail
26-Feb-10	Michele Mosca: 40 Under 40	Waterloo Region Record
26-Feb-10	Curiosity sparks quantum discoveries	Waterloo Region Record
06-Mar-10	TED goes independent in Waterloo	Imprint
Spring 2010	Driven by Curiosity: Raymond Laflamme	Motivated Magazine
09-Mar-10	Deal boosts quantum race	Waterloo Region Record
09-Mar-10	Race on to build quantum computer	570 News
10-Mar-10	Quantum tech partnership signed between UW and Singapore	Waterloo Chronicle
12-Mar-10	Artificial atoms from superconducting circuits	Imprint
18-Mar-10	Tales from the Quantum Frontier	MSNBC Science
1-Apr-10	UW signs exciting agreement!	SNAP Kitchener-Waterloo
Apr – 10	Institute for Quantum Computing: People and Place	Watch Magazine
Spring 2010	Nanotechnology in Canada	NANO Magazine
10-Apr-10	Science Show	ABC National Radio
17-Apr-10	Here in quantum country	Waterloo Region Record
Apr-10	Inspired group of 20-somethings empower change by knowledge-share	Exchange Magazine

#### UW MEDIA COVERAGE

07-May-10	Physics department builds cosmology group	UW Daily Bulletin
19-May-10	TQC 2009 underway at IQC	wrtpark.uwaterloo.com
29-May-09	Lectures in Quantum Information	UW Daily Bulletin
08-Jun-09	Lazaridis gifts to UW reach \$101M	UW Daily Bulletin
17-Jun-09	Spotlight on quantum cryptography	nanowerk.com
18-Jun-09	Spotlight on quantum cryptography	wrtpark.uwaterloo.com
18-Jun-09	New role for Lazaridis at convocation	UW Daily Bulletin
22-Jun-09	Tangled up in photons	Engineering.uwaterloo.ca
22-Jul-09	Laflamme talks on research and giving	UW Daily Bulletin
13-Aug-09	Two week course in quantum information processing	science.uwaterloo.ca
26-Aug-09	Premiere visits UW: now that's networking	UW Daily Bulletin
23-Oct-09	Gold medals at tomorrow's convocation	UW Daily Bulletin

06-Nov-10	The next big (very small) thing	UW Daily Bulletin
07-Jan-10	Quantum Grad Programs start this fall	UW Daily Bulletin
04-Feb-10	Dr. Wilhelm and the quantum device theory group	Iron Warrior
10-Mar-10	Quantum link with Singapore institute	UW Daily Bulletin
16-Apr-10	Grad students collect NSERC scholarships	UW Daily Bulletin