www.iqc.uwaterloo.ca

May 21, 2009

Developing Quantum Information to become the economic engine of the 21st Century

Prepared for Industry Canada

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Preface

This report has been prepared with three broad goals in mind:

1. Fulfill the reporting requirements of Industry Canada viz.,
    a. Providing a statement of objectives for the coming year,
    b. A description of proposed activities and how the Institute intends to implement them
    c. Identifying key milestones and related target dates for the objectives
    d. Providing a risk assessment and related mitigation strategies for the objectives

   This information can be found in Section 6 of the report.
2. Provide an overview of IQC's accomplishments in the past year. Starting next year Industry Canada will require an assessment of performance relative to the goals identified this year. Section 8 of the report, the Appendices, provides information on the Institute's accomplishments in 2008/09.
3. Provide a comprehensive assessment of the Institute relative to its research, teaching and outreach strategies, as at April 30, 2009.

1. Executive Summary

Research at IQC is focused on quantum computing and communication at both theoretical and experimental levels. Within each level, we can think of the research tackling three intertwined paths. First, there are the algorithms and protocols, which address how to control quantum information processors and how we would use them; second, we have building blocks that make proof-of-principle experimental demonstration of how we can control quantum effects for information processing; and third, there is the integration of the various parts to turn proof-of-principle experiments into quantum technologies.

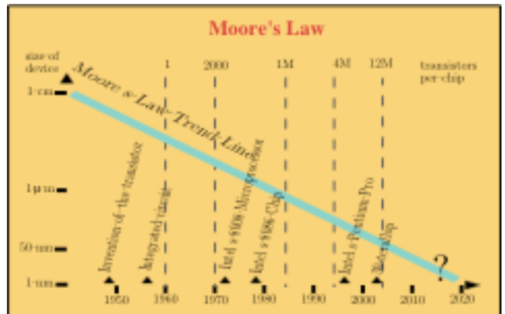
In the coming year, the focus in the direction of algorithms and protocols will be on quantum walk algorithms, quantum control and foundations/tests of quantum mechanics. For building blocks, we will investigate elements of blueprints for quantum computers such as magnetic quantum bits (qubits), photonics and superconducting materials both for quantum computing and quantum cryptography. Finally, on the path of integration, we will focus on quantum key distribution (QKD), a branch of quantum cryptography and a promising application of quantum technologies. Building on our recent QKD prototype, we will investigate the possibility of placing single photon sources on a satellite, allowing us to explore global quantum communication. Research results will be communicated to the academic world both through the usual peer-reviewed journals and through international workshops and conferences.

We have devised a strategy to attract the best students to IQC, not only by taking advantage of the strength and breadth of our research, but also through a series of summer schools, workshops and tours targeted to students, and a nascent graduate program.

Furthermore, over the next year IQC will undertake various initiatives including the development of a graduate program, our outreach plans, and the construction of a new building to house the IQC, in addition to communications, information technology and financial strategies.

2. Background

Each force of nature that has been harnessed has had a lasting impact on society. Fire, steam, electromagnetism and the splitting of atomic nuclei represent the most compelling examples. What could be the next force of nature that we can harness? What forces remain untamed? As soon as electronic computers were first built (in the 1950s), scientists and engineers tried to build faster and better models. The industry quickly realized that by making transistors smaller, they could process information faster. In 1965, Gordon Moore observed that the size of transistors decreased by a factor of two every 18 to 24 months. This observation which came to be Moore's Law, predicts that by 2020 we will have transistors the size of individual atoms. The ever-dwindling size of technologies is true not only for information processing but also for a wide variety of applications from the cosmetics industry to molecular electronic switches. Nanotechnology commonly refers to the fabrication, study, and manipulation of structures having sizes in the range of one to one hundred nanometres [a nanometre (nm) is a billionth of a metre]. This realm bridges the important gap between atoms and molecules (which range from less than one to several nm in size) and bulk materials, requiring knowledge and applications from molecular chemistry and quantum physics. The research is inherently multi-disciplinary, bringing together researchers from the faculties of mathematics, science and engineering.



The size of transistors is decreasing rapidly, around 2020 they will be of atomic size.

The behavior of bulk materials that we use every day is adequately described by what we call "classical" laws. At the atomic scale, however, we need to use a different set of rules to describe the behavior of light and matter: quantum mechanics. Quantum mechanics was discovered early in the 20th century but it is only recently that we have understood that it is much more powerful than the classical laws for manipulating information . As transistors shrink, quantum effects will come into play, and we will need to start using quantum rules to describe them.

If we ignore this quantum reality, our computers will become increasingly unpredictable as we continue to shrink them in size to make them faster. When devices get sufficiently small, quantum effects will become inevitable - by the laws of physics, and that is a pressing reason why we must invest in understanding and controlling quantum systems. In return we will open the door to the very powerful information processing possible with quantum effects.

The quantum information program will allow us to exploit quantum effects to advantage rather than regarding them as limitations. Quantum behavior produces novel properties with no counterpart in today's computer. The laws of quantum behavior, called quantum mechanics for short, allow for systems to be in a multitude of states at once and to achieve incomparable parallelism. This property allows us to solve mathematical problems which were once thought to be intractable, to develop unbreakable encryption for data that needs to be secure, to build time-keeping devices with unparalleled precision, to make ultra-sensitive detectors with tremendous accuracy, and much more.

3. IQC Vision and Strategic Objectives

Vision of the Institute
Harnessing quantum mechanics will lead to transformational technologies that will benefit society and become a new engine of economic development in the 21st Century.

Mission of the Institute
The mission of IQC 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
The IQC strives:

- To establish Waterloo and Canada as the world centre of research in quantum technologies and their applications by bringing together the best researchers from mathematics, science and engineering.
- To become a magnet for the best undergraduate, and postgraduate students and postdoctoral researchrs to engage in research activities that significantly advance quantum information science, and widely disseminate their results.
- To become a 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.

The rest of this document outlines how we have made progress in achieving these goals, but in very brief, IQC has gained a better and better reputationin the world. In 2006 and 2008 expert Reviewers were asked by Industry Canada to carry out a review of the Institute and its strategic operational plans for the future. The following comments highlight the positive view of IQC by the Expert Reviewers:

"In 2006 the review panel believes IQC to be the best institution of its type in the world. Since then IQC has made further impressive progress and there is every indication that its aggressive expansion plan will continue to give IQC, and therefore Canada, sustained world leadership."

"IQC is arguably the leading achiever in the world in its field of endeavor, on all fronts."

"The overall consensus is that IQC is a world leader in quantum computing and has continued to make impressive progress towards its vision of becoming the world leader in quantum information science and meeting the strategic objectives they set out for themselves."

4. Governance

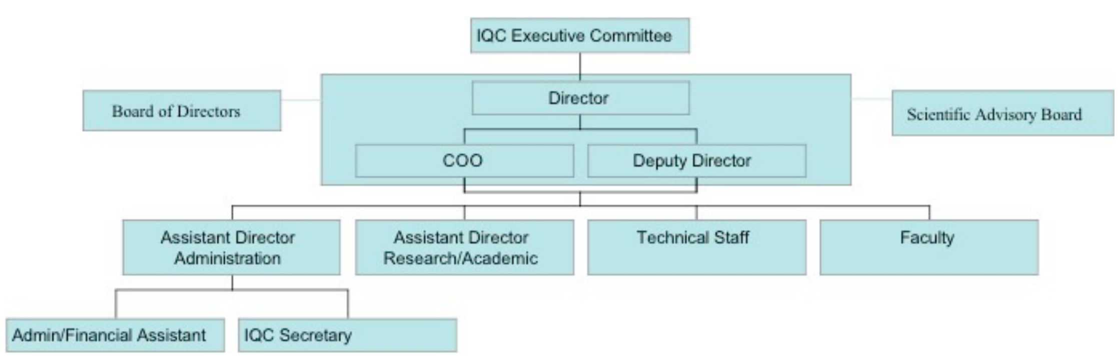
Advisory Board

IQC currently has 12 members on the Advisory Board. They are listed below:

- H. Douglas Barber – Professor Emeritus, McMaster University
- Tom Brzustowski – Chair of the Board, IQC
- Paul Corkum – Director, Attosecond Science, National Research Council of Canada
- George Dixon – Vice-President, University Research, University of Waterloo
- David Fransen – Consul General, Canadian Consulate General in Los Angeles
- Peter Hackett – President & CEO, Alberta Ingenuity
- Raymond Laflamme, Director, IQC
- Mike Lazaridis – President & Co-CEO, Research in Motion
- Steve MacDonald – COO, IQC
- Michele Mosca – Deputy Director, IQC
- Peter Nicholson – President & CEO, Council of Canadian Academies
- William R. Pulleyblank – Vice-President, Centre for Business Optimization, IBM

The University of Waterloo created IQC in 2002. Typically, a university-based institute would be nested within a department within a faculty. Given QIP's interdisciplinary nature, IQC's faculty members are appointed in six departments (Combinatorics & Optimization, Computer Science, Applied Math, Physics, Chemistry, and Electrical and Computer Engineering) spanning three Faculties (Mathematics, Science and Engineering). Clearly, an innovative approach to governance was called for. As a result, UW has created an IQC Executive Committee, chaired by the VP Research, and comprised of the deans of Mathematics, Science and Engineering, and IQC's senior management team. IQC has a truly extraordinary Board of Directors, comprised of internationally recognized leaders from academia, business and government. Sensing the enormous potential of IQC and intrigued by the opportunity to participate in the definition of its growth strategies, these Directors provide strategic advice on all aspects of management, including finances, planning, commercialization, and outreach (http://www.iqc.ca/people/bod.php). Finally, the Scientific Advisory Committee, made up of leading international scientists, including 2003 Nobel laureate, Sir Anthony Leggett, provides scientific advice on recruitment, research projects and the overall research plan (http://www.iqc.ca/people/?w=06).

IQC's organizational chart:



IQC has a process to evaluate and give feedback to the faculty. In a typical University setting, institutes and faculty members are part of a department and departments do their annual evaluations. At IQC, faculty are jointly hired with departments and up until last year, the evaluations were done solely by the departments. As mentioned above, a pilot project was started last year to evaluate research, outreach and contributions to IQC. This year, the evaluations will be sent to head of departments and will also be used in the renewal process for IQC membership.

IQC members are elected for 5 years; for this they receive some teaching relief and a stipend. Process for renewal has been put in place and the first renewal of membership is now happening. The process is as follows:

1) The Director will ask a senior member of IQC to make the case for a member to be renewed.

2) The Director will ask the candidate for an updated CV, research proposal for the next 5 years, a one page statement of what IQC has brought to the member, how the member believes they will contribute to IQC in the next 5 years and 3 proposed referees, from which 2 will be chosen.

3) The senior member will put forward a recommendation through a memo outlining the case (renewal or not), and the senior member will ask for 2 more letters.

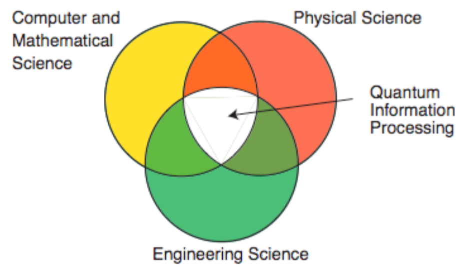
4) The director will bring the case to the scientific advisory committee and ask advice about the recommendation.

5) The case will be brought to the board.

5. Research Focus

Background

Research is and has been at the heart of IQC's strategy to establish itself as a world leader. It is, not surprisingly, focused on both theoretical and experimental quantum information science and technology. It encompasses the broader areas of computer science, mathematics, physics, chemistry and engineering. There are three main themes of research: algorithms and protocols, experiments, and integration of both theoretical and experimental components. Building on the recent research successes and the new faculty arrivals at IQC in the last year, below we describe projects in each theme in more detail.



Algorithms and protocols

This theme primarily addresses the following question: if we had quantum information processing devices today, what would we do with them? This theme is theoretical in nature, but can involve the use of feedback from experiments. It includes research on the degree of difference between quantum and classical information processing. It also addresses questions on how to make quantum devices more robust with respect to error, either due to imperfection of the control or impact of their surroundings.

At the foundation of quantum information science is the belief that it allows us to solve some problems using much fewer resources than with a classical computer.
In order to do this, a detailed resource assessment and a classification of problems are needed, leading to the field of quantum complexity theory. Researchers at IQC are making breakthroughs in this area. This research also entails what is possible and not possible with quantum computers, i.e. understanding their limitations.

The most famous quantum algorithm, discovered by Shor about fifteen years ago, is designed to factor numbers that are products of primes. This has critical implications for today's cryptographic systems. Having a large quantum computer today would allow eavesdropping on most (public-key) cryptographic systems in use at the present time. Much progress has occurred since Shor's discovery, and new quantum methods and techniques have been discovered, providing new algorithms. IQC has good-sized group of researchers investigating algorithms, and they have contributed to many of these recent advancements.

One family of algorithms is the quantum random walk. Random walks are useful tools for classical computers to search for solutions to problems in computer science, physics, ecology and economics, in particular when random processes are at work. It turns out that the quantum version of random walks allows for more efficient solutions. This is a very active area of research and IQC will contribute to it. An interesting new idea is the quantum snake algorithms. Usually quantum walk algorithms focus on reaching a point in a graph, but in quantum snake algorithms the goal is to find a path. This is a new direction that has potentially important applications for pattern recognition.

Other potential applications of quantum walks are large-girth Cayley graphs, scattering algorithms,span programs, directed graphs and mixing on graphs. They will be studied in th coming years.

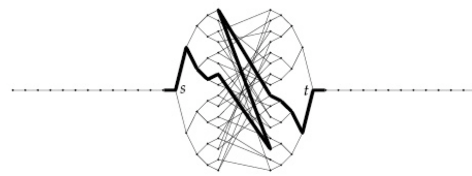


Figure 1: A snake algorithm finds a path instead of reaching a point in a path. Research will aim to determine if the quantum version is more efficient than the classical one.

One of the reasons why it is very hard to predict the behavior of quantum systems with the tools we have today is that it is difficult to simulate quantum systems using classical computers. One of the applications of quantum computers is to simulate quantum systems. This could have great benefits in areas such as chemistry, material science and drug design, where it could be possible to build and understand a larger and larger base of information from the ground up. IQC researchers have had success in this area and will continue to pursue this research direction.

An important area of theoretical research that is getting strong experimental feedback is the control of quantum systems, an essential ingredient in building quantum technologies. Many rules of quantum mechanics are profoundly different from those in the classical world. One such example is that it is impossible to extract information from a quantum system without perturbing it. It turns out that this property is at the basis of the quantum key distribution (a branch of quantum cryptography). However, this same property makes life difficult when we try to control quantum systems. In fact, until recently, it was thought that it would be impossible to control them reliably. In 1995, quantum error correcting codes that protect quantum information from corruption were discovered. Building on this work researchers showed that not only could the memory of quantum computers be protected, but this robustness could be transferred to the logical operations. There are still important questions to be answered, such as: what kind of noise can be corrected; what is the amount of noise that can be tolerated; what is the minimal amount of extra resources that is needed? Another point is how to achieve sufficient control to be able to implement quantum error correction protocols. Researchers at IQC are actively seeking answers to these questions.

Implementations

Since its inception, IQC has created an experimental quantum information processing program with a focus on spin qubits, in particular in liquid and solid state Nuclear Magnetic Resonance (NMR). We have expanded to accommodate groups covering more experimental areas, including optics, with one group focused on quantum key distribution and the other on multi-photon entanglement; a group working on quantum dots; and groups working on superconducting devices.

One of the first proposals for a quantum processor has been through NMR technology. Using the magnetic moment of atoms in molecules to encode quantum information, NMR technology has been able to control up to a dozen qubits. This allowed us to develop methods of control in a realistic setting and understand how they can be implemented. The work in NMR was initially performed in the liquid state and has recently been expanded to include work on the solid state. In both liquid and solid states, the emphasis has been on implementing ideas of quantum error correction protocols and testing their assumptions.

In particular, work has been done to determine the error model of quantum devices – a task that is intractable if done exactly. A series of protocols have been devised which give information necessary to implement quantum error correction codes. In a similar vein, we have devised methods to characterize noise in the presence of gates. Recently, they have been implemented in an NMR quantum information processor. We are also proceeding with a comparative analysis of the benchmark results for a variety of platforms.

The work in NMR is being extended to include magnetic systems where electrons and the nuclei are being manipulated. It is possible to do so using similar systems to those used in solid state NMR and also in quantum dots. The advantage of using electrons is that they interact much more strongly than the nucleus and thus allow for faster operation of the quantum device. On the other hand this leads also to an increased corruption rate. We are investigating the compromise needed to deal with these two processes.

Another platform for quantum information processing that is being investigated at IQC is photonics. Photons, or particles of light, are excellent qubits (physical systems that encode bits of quantum information) as they can robustly encode quantum information and are easily produced. Quantum systems can be entangled, meaning that they can have correlations that cannot be explained by classical laws of physics. Researchers in quantum photonics have been producing entangled photons for some years now, but the quest to have ever-larger systems of entangled photons persists. At IQC, we will develop new sources of entangled photons that will be used in quantum computation and communication experiments at the Institute.

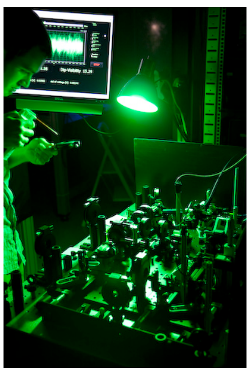


Figure 2. Researchers at IQC uses photons to the encode and process of quantum information

At low enough temperatures, some materials exhibit essentially zero electrical resistance, in a phenomenon called superconductivity. It is fundamentally a quantum phenomenon that researchers have known about for years, but it is only recently that these materials have been used for quantum information processing. One application is to fabricate large, extremely sensitive bandwidth detectors for photons called SNSPD. The fundamental process leading to superconductivity is the pairing of electrons (Cooper pairs) in materials. The detectors built at IQC rely on photons breaking the bond between pairs and creating a temporary increase in the electrical resistance of the material. In the coming year IQC will adapt these detectors and use them in quantum photonic experiments conducted at the Institute.

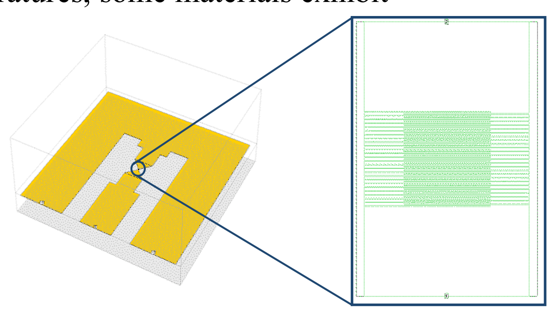


Figure 3. Sonnet ® schematic representation of an SNSPD and its surrounding tapered gold coplanar waveguide with three pads (G-S-G). The overall device is about 3 mm by 3 mm. The insert shows a magnification of the meandered structure.

A second use of superconductivity is to create another type of qubit. By making rings of superconducting material, we can generate an electrical current that will create a magnetic field. From there, it is possible to encode a qubit of information in the magnetic field. IQC has recently hired a new faculty member whose goal it is to fabricate and use circuits of superconducting material for quantum information processing.

In an effort to allow some of our key research initiatives to move forward, particularly in the areas of quantum dots and superconducting material, we have begun to construct a nanofabrication (nanofab) facility in the IQC's current headquarters on the university's north campus. This temporary cleanroom will have a lower certification level than the cleanroom that will eventually be part of the Quantum-Nano Centre, but it will certainly be adequate as an important first step to create several types of devices needed for the research initiatives in question.

The temporary nanofab will house approximately $5M worth of the $28M in scientific equipment funding granted for this project. The fabrication equipment will be installed over the course of the summer and fall 2009. Some of the major components of the toolset to be installed include an electron-beam lithography system for writing patterns as small as 15 billionths of a metre across, two physical vapour deposition systems for depositing various types of materials such as aluminum, iron and germanium, and two inductively coupled reactive ion etch (ICP-RIE) systems which will allow for the selective etching of a very large assortment of materials ranging from metals to insulators to semiconductors.

The equipment, which we will soon have access to, is similar to the types of machines typically used to manufacture integrated circuits and MEMS components, such as those found in many consumer products today (the Nintendo Wii handset for instance). Our aim is to adapt these fabrication technologies to manufacture various types of devices needed by our researchers such as include superconducting Josephson junctions and quantum dots.

Integration

One of the most advanced quantum technologies is quantum key distribution (QKD). The goal of QKD is to exchange (more precisely, expand) a key between two interlocutors in order for them to be able to exchange private information. A detailed introduction about QKD and the state of the technology in the world can be found at www.iqc.ca/~laflamme/reports/CSEReport.pdf. QKD is often mentioned as the low-hanging fruit of quantum technologies. A few start-up companies have already been created, and companies such as HP, IBM, NEC, Toshiba and NTT have active group investigations into various aspects of these technologies.

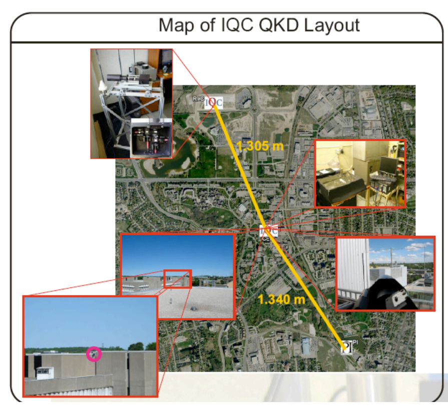


Figure 4 Operational quantum key distribution system at the IQC. A source of entangled photons is sent from the CEIT building at the university, reaching both the IQC and the Perimeter Institute where keys are established and tested for eavesdropping.

A QKD system would make use of many of IQC's capabilities – the theoretical group, sources of entangled photons and superconducting detectors mentioned above – and integrate them in a common system. IQC is well placed to make breakthrough in this new technology.

One of the weak links of QKD is its distance limitations. The absorption rate of photons going through optical fibres has limited point-to-point key distribution to about one hundred kilometres. One potential solution is to use quantum repeaters that would correct for errors during transmission and extend the distance with a reasonable amount of overhead. Although we know how to theoretically devise quantum repeaters, only simple proofs-of-experiments are available in the lab and thus QKD is at present, distance limited.

Another QKD implementation is based on using free space as a communication link. It is usually limited through the line of sight between the source and the interlocutors but it could be possible to place the source in a way to extend the distance limitation present in optical fibres systems.

In the last two years researchers at the IQC have built and operated a QKD prototype. It has allowed IQC researchers to have hands-on experience with the devices, particularly with determining their security in a practical setting.

A project that IQC will focus on is studying the possibility of placing a source of photons on a satellite and allowing quantum communication in space in collaboration with the Canadian Space Agency (CSA). Combining the CSA fast-tracking optical terminals and IQC quantum transceivers will advance quantum communication technology and form a basis for the design of future quantum communication space missions.

6. Objectives

This section identifies IQC's objectives for the next fiscal year (May 1, 2009 through April 30, 2010).

Each objective starts with some context and a goal statement, and then the goal is tied to IQC's strategic plan. Next, key milestones and related target dates are set out with expected results. Finally risk assessment and mitigation plans are outlined.

The objectives for next year include:
1. Research
2. Graduate Program and Teaching
3. Outreach
4. IQC Building
5. Communications
6. Information Technology
7. Financial

IQC's leadership team – Raymond Laflamme, Mike Mosca and Steve MacDonald – meet weekly to discuss IQC's strategic and operational issues. The objectives identified in this report are key success factors for IQC, and will be monitored at these meetings.

6.1 Research

Background
The research conducted at IQC is focused on both theoretical and experimental quantum information science and technology. It encompasses the broader areas of computer science, mathematics, physics, chemistry and engineering. There are three main themes of research: algorithms and protocols, experiments, and integration of both theoretical and experimental components.

IQC's research team currently consists of 18 faculty, 20 postdoctoral fellows, and 65 graduate students and undergraduate research assistants.

Objectives
Research at IQC is focused on quantum computing and communication at both theoretical and experimental levels. Within each level, we can think of the research tackling three intertwined paths:

- First, there are the algorithms and protocols, which address how to control quantum information processors and how we would use them;
- Second, we have building blocks that make proof-of-principle experimental demonstration of how we can control quantum effects for information processing;
- Third, there is the integration of the various parts to turn proof-of-principle experiments into quantum technologies.

In the coming year, the focus in the direction of algorithms and protocols will be on quantum walk algorithms, quantum error correction and foundations/tests of quantum mechanics. For building blocks, we will investigate elements of blueprints for quantum computers such as magnetic quantum bits (qubits), photonics and superconducting materials both for quantum computing and quantum cryptography. Finally, on the path of integration, we will focus on quantum key distribution (QKD), a branch of quantum cryptography and a promising application of quantum technologies. Building on our recent QKD prototype, we will investigate the possibility of placing single photon sources on a satellite, exploring global quantum communication. Research results will be communicated to the academic world both through the usual peer-reviewed journals and through international workshops and conferences.

We have devised a strategy to attract the best students to IQC by taking advantage, not only of the strength and breadth of our research, but also through a series of summer schools, workshops and tours targeted to students and a nascent graduate program.

The IQC mission statement states that, "Our mission is to aggressively explore and advance the application of quantum mechanical systems to a vast array of relevant information processing techniques."

The strategic objectives of research at IQC are:

- To establish Waterloo and Canada as the world centre of research in quantum technologies and their applications by bringing together the best researchers from mathematics, science and engineering.

- To become a magnet for the best undergraduate, postgraduate and postdoctoral students to engage in research activities that significantly advance quantum information science, and widely disseminate their results.

Milestones and Timeline
For April 2010:

Hire 2 additional faculty
Hire 8 postdoctoral fellows
Hire 20 research students
Write more than 100 research papers
Organize 3 scientific workshops and/or conferences
Give more than 100 scientific presentation talks
Host 50 research seminars
Install equipment in nanofab facility

Expected Results
Results expected as above.

Risk Assessment
The primary risk to our ultimate objective is if IQC fails to add to its complement of researchers and to encourage these researchers to communicate and collaborate in their work.

6.2 Graduate Program and Teaching

Background

UW has been offering courses in quantum information since Winter 2000, and several of these courses are now standard offerings in several departments and faculties. The core course, “Introduction to Quantum Information Processing,” has been split into undergraduate and graduate sections due to overwhelming demand. Appendix F lists all future, current and previous courses in quantum information taught by IQC faculty.

IQC faculty (and associate faculty) have over this period supervised over 40 completed graduate theses in quantum information through the 6 units (School of Computer Science, Combinatorics & Optimization, Applied Mathematics, Physics & Astronomy, Chemistry, Electrical & Computer Engineering) and are currently supervising 50 theses in progress.

Several universities are forming, or have recently formed, graduate programs in quantum information (e.g. MIT, Imperial College, National University of Singapore, Max Planck Institute of Quantum Optics).

We now have a sufficient number of faculty and base of courses in quantum information to launch a strong graduate program. We are developing more detailed plans to launch a graduate program in quantum information at IQC, and will also introduce additional opportunities to engage students at the undergraduate and high school level. This will include new Masters and PhD programs focusing on quantum information, with the opportunity for various specializations.

Objectives

One of IQC’s strategic objectives is to become a magnet for the best undergraduate, postgraduate and postdoctoral students to engage in research activities that significantly advance quantum information science, and widely disseminate their results.

Having a graduate program in quantum information will serve several important purposes.

First, it will facilitate the advanced training of graduate students in quantum information and the various related disciplines. The program will nurture a new generation of researchers with a broader and deeper understanding of the field of quantum information.

Furthermore, advertising a quantum information program will be an excellent recruitment tool for prospective graduate students around the world. It will both encourage students to pursue research in quantum sciences, in particular in quantum information and related subjects. It will also encourage them to pursue these studies in Canada at Waterloo.

Finally, having a dedicated program will streamline the recruitment of quantum information students (since students can directly apply to the program).

Timeline

IQC has recently hired a contract staff person to work full time with Michele Mosca to plan the program and prepare an Ontario Council of Graduate Studies proposal for a new graduate program (both Masters and PhD). Our target submission date is Fall 2009.

Expected Results
We anticipate that the Ontario Council on Graduate Studies (OCGS) will approve the program by Summer 2010. Worldwide advertising will start in 2010, and relevant academic committees will be formed. New students will enter the program in 2011.

Risk Assessment
The most obvious risk is that internal negotiations for setting up the program delay the preparation of the OCGS proposal beyond Fall 2009. In this event, we hope to submit by Winter 2010. We would still be able to advertise the program pending approval.

Another risk is that OCGS rejects the proposal. While we don't think this is likely, the contingency plan would be to resubmit a revised proposal based on the feedback. With regard to students that applied for the proposed program, we would seek to obtain positions for the top students in the existing related programs at UW. In the immediate future we would continue to use the existing programs, until a new program is eventually approved and launched.

A project plan for the graduate program has been prepared and progress is tracked at weekly meetings.

6.3 Outreach

Background
To complement the research that has been done at IQC, we have organized meetings, workshops, outreach activities and conferences. Some of these are highly specialized, with topics such as security proofs in quantum cryptography, but others, including public lectures, are more general.

In addition to these activities, there is a strong visitor program that has brought more than 700 visitors since the inception of IQC; Appendix C contains a list of visitors. These visitors include researchers, students and teachers, business partners, journalists and members of government agencies.

Objectives
As part of our strategic objectives, IQC strives "To become a 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."

Reaching out to its communities – both Waterloo and the international scientific community – will assist IQC in attracting the best and brightest students and researchers.

Milestones and Timelines
1. 4th Workshop on Theory of Quantum Computation, Communication and Cryptography – May 11-13, 2009
2. Undergraduate School on Experimental Quantum Information Processing – June 1-12, 2009
3. Quantum Cryptography School for Young Students – July 21-31, 2009
4. Fields Institute workshop (Mathematics in Experimental Quantum Information Processing) – August 10-14
5. 4th annual Sir Anthony Leggett Lecture Series – Summer 2009

Expected Results
We expect that, through our outreach programs, both the scientific and lay communities will become increasingly aware of IQC and its activities. As an additional benefit, we expect that outreach will help to attract excellent researchers and students from around the world.

Risk Assessment
In order to entice participants to attend these conferences, presenters should present material that is new, relevant and challenging to the field. Our researchers at IQC are on the cutting edge of quantum information, and through their own work and connections across the globe, are able to provide the necessary intellectual weight to encourage leading scientists to attend.

The conferences must also be flawlessly executed, requiring a consistent degree of commitment from organizers so that attendees have their needs met in order to fully benefit from the community atmosphere and the material being presented.

6.4 IQC Building

Background
The future home for IQC, currently under construction, is part of the Quantum Nano Centre (QNC). It is located at the heart of the university. The QNC is a 284 thousand square foot, five storey facility with a 10 thousand square foot clean room, and 20 thousand square feet of laboratory space. The IQC share of the building cost is $80 million.

Objectives
These objectives were guided by two of IQC's strategic objectives:

1. To establish Waterloo and Canada as the world centre of research in quantum technologies and their applications by bringing together the best researchers from Mathematics, Science and Engineering.
2. To become a magnet for the best undergraduate, postgraduate and postdoctoral students to engage in research activities that significantly advance quantum information science, and widely disseminate their results.

The design of the building was guided by three principles:

1. The need to be functional and in particular to adhere to stringent requirements related to temperature control, low vibration and electromagnetic radiation;
2. Induce interaction between members of IQC; and
3. Serve as an attractor.

The primary goal now is to ensure the building gets constructed per specifications, on time and on budget.

Milestones and Timeline
The building is scheduled for completion early 2011. Milestone dates for the next year include:

1. Forming the ground floor slab	May 2009
2. 2nd floor slab	June
3. 3rd floor slab	July
4. 4th floor slab	August
5. 5th floor slab	October
6. Super structure	November
7. Building envelope completion	March 2010

Expected Results
It is expected that the building milestones will be completed on time, on budget and as per specifications.

Risk Assessment
This complex facility will face challenging environmental, financial and engineering and practical change management issues. To mitigate these risks, bi-weekly project management meetings take place with the contractor, the architect, university personnel that have direct responsibility for the project. Further, a steering committee meets quarterly or as required to ensure the mandate, as summarized in the objectives, is met. Also, the budget provides for a five per cent construction contingency.

6.5 Communications

Background
It is IQC's strategic objective, "To become a 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. " The leadership team at IQC identified Communications as their highest administrative priority. To further this objective a Communications initiative is being undertaken.

Objectives
The purpose of the communications initiative is to develop a road map to fulfill IQC's strategic objective of becoming *the* source of quantum information. The map will identify the target audiences, and the processes and tools required to achieve alignment with the strategy. This will involve the development of a strategy to create the IQC brand. This in turn entails identifying the unique IQC culture, knowing our key stakeholders and their information requirements, and becoming an aggregator of quantum information. And finally, we will need to identify outreach partners to work with in order to get the message out.

Milestones and Timeline
Milestones and the related dates for the next year include:

1. Select working team members/kick-off meeting	July 2009
2. Gather feedback from key stakeholders	October
3. Establish initial priorities to focus Communications efforts	November
4. Set Communications budget	December
5. Decide on Communications people structure	January
6. Decide key messages (themes, look & feel, branding)	April
7. Identify/develop tools to use for communication	May 2010

Expected Results
The stakeholder engagement process will inform the strategy and will help focus efforts to areas that will advance the objective of becoming *the* source of quantum information. Once the direction is set, the skills required to deliver the strategy will become clear. This in turn will lead to the development of an IQC brand and to clarity around the methods or tools to use to become *the* source of quantum information, analysis and commentary.

Performance will be assessed based on meeting target dates and the feedback of stakeholders. A future measurement will be the growth in volume of traffic on our web site. A baseline will be established as part of the information gathering process.

Risk Assessment
This initiative faces financial and human resource risks. Further, because branding is so judgmental, making a decision on themes, look and feel and tools could become complex. To mitigate the financial and human risks, project plans and budgets will be established and bi-weekly project management meetings will be set up to track performance against the plan, and to ensure resources are focused on key deliverables. To assist the decision making process around branding, principles to inform decision making will be developed prior to initiating discussions on the brand.

6.6 Information Technology

Background
As IQC has grown rapidly since its inception in 2002, it is not surprising that its administrative capabilities lag behind the needs of the scientists, students and administrative staff. Information Technology is an integral aspect of the administrative infrastructure for the Institute, and it has been identified as the primary area in which the administrative team can further support the IQC mission.

Objectives
These objectives were guided by one of IQC's main objective: to become a 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.

The purpose of the Information Technology (IT) initiative is to develop a road map for the delivery of IT that aligns with IQC's scientific mission. The road map will spell out the people, processes and tools required to achieve alignment. This will involve the development of a strategy for the IT portfolio components, viz. infrastructure, transactional, information management and strategic technology. Ideally many of the strategy components will be implemented concurrently. Realistically, the plan is to start at the foundational level and move towards the more strategic elements over time.

Infrastructure includes the server architecture, communication systems and client service standards. This component of the strategy will define the service standards for how IT operates at IQC, and our relationship with the University of Waterloo's IT departments.

Transactional and information management systems include inventory tracking, groupware and financial data base tools. The delivery of robust end user tools will better enable the scientists, students and administrative staff to collaborate and interpret information.

Milestones and Timeline
Milestones and the related dates for the next year include:

1.	Engage stakeholders in IT strategy development	Summer 2009
2.	IT strategy approval	September
3.	Implement one piece of infrastructure	January 2010
4.	Implement a second piece of infrastructure	April
5.	Implement a transactional component	June

Expected Results
The stakeholder engagement process will inform the strategy and will help focus efforts to areas that will provide the scientists with resources that most enable their work. The strategy will provide the road map to guide implementation. Implementing components will lead to tools end users will benefit from either directly (e.g., groupware) or indirectly (e.g., enhanced data security). Performance will be assessed based on meeting target dates and feedback from end user surveys.

Risk Assessment
This initiative faces financial, human and scope creep risks. To mitigate these risks, project plans will be established for each initiative and bi-weekly project management meetings will be set up to track performance against the plan, and to ensure resources are focused on key deliverables.

6.7 Finance

Background
The financial viability of IQC has been strengthened by the tremendous support received by the federal and provincial governments, private benefactors and the University of Waterloo. The recent announcement of $50 million in Industry Canada funding has removed much uncertainty as to the ongoing sustainability of the Institute.

The leadership team at IQC has identified the need for a financial plans for the new IQC building to be finalized, the need for a financial plan to fund the equipment that will be used in the fabrication facility and in the labs, and critically, a plan that addresses the ongoing operational sustainability of the research efforts.

Objectives
The purpose of the financial initiative is to document the funding requirements to complete the construction of the building, to equip the facility with state of the art equipment, and to document the funding required to support the strategic objectives of IQC. The financial planning will entail documenting the source of funding, estimating capital and operational charges, as well as investment income and future funding needs, and potential new sources of funding as required.

Milestones and Timeline
Milestones and the related dates for the next year include:

1. Finalize funding plans for the IQC building	June 2009
2. Prepare a financial plan for equipping the facility	July
3. Prepare a 10-year financial plan for ongoing operations	November
4. Draft a proposal to address funding shortfalls	March 2010

Expected Results
The financial plans will identify IQC's cash flow requirements and any shortfall in funding that will limit the Institutes ability to achieve its vision and related strategic objectives. This will lead to a clear understanding of ongoing support required to sustain operations, and will inform further planning if and as required.

Risk Assessment
Naturally the primary risk is that IQC presently has insufficient funding to meet its strategic objectives. The primary purpose of updating the cash flow analysis is to determine the size of the exposure, and to prepare mitigation strategies as applicable.

The leadership team and the Board will oversee each stage of this initiative.

7. Five Year Budget

The chart below provides an overall picture of IQC's financial plan for research, operations and building construction over the next 5 years. The present year, as at April 30, is included for reference purposes.

IQC total budget ($millions)						
	08/09	**09/10**	**10/11**	**11/12**	**12/13**	**13/14**
# of faculty	18	20	21	23	26	30
Expenses						
Operations/Research	7.5	9.2	10.4	11.8	13.7	16.2
Building	18.6	37.5	23.9			
Total	**26.1**	**46.7**	**34.3**	**11.8**	**13.7**	**16.2**
Revenues						
University of Waterloo	4.3	2.2	2.9	3.8	5.2	7.2
Federal	0.0	16.5	17.0	5.0	5.5	6.0
Research Grants	3.2	3.0	3.0	3.0	3.0	3.0
From Building Fund	18.6	25.0	11.4			
Total	**26.1**	**46.7**	**34.3**	**11.8**	**13.7**	**16.2**
Assets						
Building Fund 55.0	36.4	11.4				
Endowed/Trust 84.0						

The building fund includes the following contributions totaling $80 million:

Government of Ontario	$42.9
Mike Lazaridis	$8.7
Canada Foundation for Innovation (CFI)	$3.4
Federal Government	$25.0

The endowment/trust, totaling $84 million will come from:

Mike and Ophelia Lazaridis	$27.3
Province of Ontario	$6.7
Mike Lazaridis pledge	$50.0

The endowment will cover IQC's operations and IQC's contribution to Highly Qualified Personnel (HQP) This is separate from the money coming from IQC faculty grants from 2014 onward. UW will commit the salary of faculty positions.[1]

The federal investment of $50M will be targeted towards the construction of the building ($25M, as mentioned above), $5M to equipment for IQC researchers and $20M for HQP and operation of the Institute.

[1] The budget does not include the contribution from the recent Canada Foundation for Innovation/Ministry of Research and Innovation (CFI/MRI) proposal, as it provides the equipment for the fabrication facility. The total grant is $49M, of which $36M comes equally from CFI and MRI. Most of the funding is targeted to buy fabrication and metrology equipment for that facility. There is one exception: $3.3M of the contribution will go to cover part of the cost of the IQC building.

Industry Canada Funding ($millions)					
	09/10	**10/11**	**11/12**	**12/13**	**13/14**
Building	12.5	12.5			
Equipment	1.0	1.0	1.0	1.0	1.0
People (HQP) /Operations	3.0	3.5	4.0	4.5	5.0
Total (grand total is $50M)	**16.5**	**17.0**	**5.0**	**5.5**	**6.0**

Equipment will be used towards start-up funds for future IQC faculty, which includes:
1) $750k/year for equipment and small renovations to adapt laboratories to each new faculty member. It is not possible to give a detailed description of exact pieces of equipment that will be bought as they are for start-up of future faculty
2) The other $250k/year will be used to maintain IQC's research capabilities at a level where it can compete internationally. This includes upgrades to IQC's faculty equipment, computing hardware, software, warranties and consumables.

Budget for Federal Funding ($millions)						
HQP	**09/10**	**10/11**	**11/12**	**12/13**	**13/14**	**Total**
Post Doctorate	0.5	0.6	0.8	1.0	1.0	3.9
Grad	0.3	0.4	0.4	0.4	0.5	2.0
Undergrad	0.1	0.1	0.1	0.1	0.2	0.6
Research and visiting scientist	0.2	0.2	0.3	0.4	0.4	1.5
Knowledge transfer						
Conferences	0.2	0.2	0.2	0.2	0.2	1.0
Summer school	0.1	0.1	0.1	0.1	0.1	0.5
Public Awareness	0.1	0.1	0.1	0.1	0.1	0.5
Communications	0.2	0.2	0.2	0.2	0.2	1.0
Operations						
Admin Staff	0.5	0.7	0.8	0.9	1.0	3.9
Technical Staff	0.2	0.2	0.2	0.2	0.3	1.1
General/Facility	0.6	0.7	0.8	0.9	1.0	4.0
	3.0	**3.5**	**4.0**	**4.5**	**5.0**	**20.0**

8. Accomplishments

This section highlights some of the accomplishments of the IQC and its members over the past year (May 1, 2008 to April 30, 2009). Accomplishments have been subdivided into seven categories: Hiring, Publications, Teaching and Outreach, Grants, Awards, Visitors, and the Quantum Nano Centre. Each invites the reader to refer to the appropriate appendix for more detailed information on each area.

Where applicable, we have provided comparisons with IQC's objectives for the upcoming year.

Hiring
Since April 2008, IQC has hired two faculty members, bringing the number of faculty to 18, and plans to add two more in the coming year, in keeping with the expected results outlined in section 6.1.

In the past year, seven postdoctoral researchers have moved on from the Institute. Five new postdoctoral fellows have been hired and it is expected that eight more will be added over the next year.

For a more detailed examination of IQC's team, please see Appendix H.

Publications
Since 2008, IQC members have contributed to 100 publications in refereed journals including leading periodicals such as Science, Nature, Nature Physics and Physical Review. They have contributed eight chapters to books and proceedings and have published an introductory textbook for quantum computing.

Over the next year, the Institute aims to produce more than 100 research papers, in keeping with the expected results outlined in section 4.1 of this report (Objectives – Research).

A complete list of publication citations can be found in Appendix E.

Teaching and Outreach
IQC is working towards starting a graduate program in quantum information, building on the base of courses already offered by the Institute.

Last year, the IQC offered three summer programs and conferences for students ranging from secondary to post-graduate level who were interested in learning more about various aspects of quantum computing.

This year, the IQC plans to organize at least three scientific workshops and/or conferences.

For a complete list of courses in quantum information taught by IQC faculty members since 2008, please see Appendix F. A detailed list of upcoming conferences at IQC can be found in Appendix G.

Grants
In 2008-2009, IQC received $3.2 million in grants from industry, government and academic partners. These funds are in addition to previous years extraordinary $50M donation from Mike and Ophelia Lazaridis, a $50M grant from the government of Ontario and a $36M from CFI/MRI grant for the joint fabrication facility in the QNC.

Starting next year, the IQC will receive a total of $50 million over five years from the federal government. A further $3.0 million in research grants is also expected.

A complete list of grants from 2008-2009, as well as the total of grants received since our inception in 2002, is available in Appendix A.

Awards
IQC faculty, board members, postdoctoral researchers and students received much recognition for their work over the past year.

In April 2008, IQC researcher Dr. Richard Cleve received the 2008 CAP/CRM Prize in Theoretical and Mathematical Physics.

Institute director Dr. Raymond Laflamme has had his Canada Research Chair renewed, in addition to receiving a Premier's Discovery Award and being elected as a Fellow of the Royal Society of Canada.

Earlier in 2009, new faculty member Dr. Adrian Lupascu received the largest NSERC Discovery Grant ever awarded to a newcomer and PhD student Gina Passante received NSERC's Vanier Graduate Scholarship.

For a complete list of awards received by IQC members, please see Appendix B.

Visitors
From May 2008 to April 2009, IQC hosted 129 groups of visitors, ranging from community groups to business leaders, fellow academics and members of the media.

A complete list of visitors since 2008 can be found in Appendix C.

Quantum Nano Centre
Construction of the Quantum Nano Centre, located at the heart of the UW campus, began in July 2008. It is expected that the building will be completed per specifications, on time and on budget.

For more information on the Quantum Nano Centre, please refer to Appendix K.

Appendix B: Awards

Awards received in 2009

Board of Directors

Paul Corkum	Gerhard Herzberg Canada Gold Medal for Science & Engineering

Faculty

Raymond Laflamme	Canada Research Chair Renewal
Adrian Lupasçu	NSERC Discovery Grant
Frank Wilhelm	DARPA Grant

CIFAR Inductees

Bill Coish	New Junior Fellow

Mike & Ophelia Lazaridis Fellowship

Behnood Ghamsari
Farzad Qassemi-Mallomeh
Yingkai Ouyang
Lana Sheridan

Bell Family Research Fund Award

Bill Rosgen

NSERC Awards

Gina Passante	Vanier Graduate Scholarship
Jamie Sikora	
Jamie Smith	
Jonathan Lavoie	Alexander Graham Bell Doctoral Canada Graduate Scholarship

Other Misc Awards

Chris Erven	UW's Imprint Coach of the Year Award

Awards received in 2008

Faculty

Andris Ambainis - Alfred P. Sloan Foundation Fellowship
Richard Cleve - CAP/CRM Prize
Joseph Emerson - Early Researcher Award
David Kribs - NSERC Discovery Accelerator Supplement
Raymond Laflamme - Premier's Discovery Award and Fellow of the Royal Society of Canada
Ashwin Nayak - NSERC Discovery Accelerator Supplement and a grant award from Human Resources Social Development Canada

CIFAR Inductees

Scott Aaronson	New Associate
Joseph Emerson	New Scholar
Daniel Gottesman	New Fellow
John Watrous	New Fellow

Quantum Works Inductees

Jonathan Baugh	Associate Member

Anne Broadbent	Associate Member
Andrew Childs	Associate Member
Thomas Jennewein	Associate Member
Adrian Lupascu	Associate Member
Ben Reichardt	Associate Member
Kevin Resch	Associate Member

Mike & Ophelia Lazaridis Fellowship

Devon Biggerstaff
Behnood Ghamsari
Robin Kothari
Chandrashekar Madaiah
Farzad Qassemi-Mallomeh
Lana Sheridan

Bell Family Research Fund Award

Omar Gamel
Peter Groszkowski
Gus Gutoski
Marcus Silva
Sarvagya Upadhyay

NSERC Awards

Chris Erven	Colm Ryan
Chris Ferrie	Jamie Sikora
Jonathan Lavoie	Stephanie Simmons
Easwar Magesan	Marcus Silva
Brendan Osberg	Cozmin Ududec
David Ostapchuk	Zhizhong Yan

Other Misc Awards

Devon Biggerstaff	GWPI Poster Session Winner
Jean Christian Boileau	John Brodie Memorial Award
Mohammad Derakhshani	International Masters Student Award & UW Grad Scholarship
Agnes Ferenczi	International Doctoral Student Award & Science Grad Experience Award
Gus Gutoski	David R. Cheriton Scholarship
Martin Laforest	Doctoral scholarship from Le Fonds Quebecois de la recherche sur la nature et les technologies
Easwar Magesan	President's Graduate Scholarship
Gina Passante	J. Alan George Student Leadership Award (2008)
Stephanie Simmons	Clarendon Scholarship at Oxford
Douglas Stebila	Best Oral Presentation at UW's Grad Student Research Conference

Appendix C: Visitors

Category	Date	Name	Affiliation
Government	9/1/09	Karen Corkery	Industry Canada
Academic	11/1/09	Robert Prevedel	University of Vienna
Academic	13/1/09	Susumu Susaki	Niigata University, Faculty of Engineering, Japan
Academic	18/1/09	Frederic Magniez	LRI, Orsay, France
Academic	22/1/09	Avatar Tulsi	India Institute of Science, Physics Department
Academic	24/1/09	Lawrence M. Ioannou	University of Cambridge
Academic	26/1/09	Akihito Soeda	University of Tokyo
Academic	26/1/09	Sean Hallgren	Pennsylvania State University
Business	30/1/09	Claude Jean	Dalsa
Academic	4/2/09	Raisa Karasik	Berkeley, University of California
Academic	9/2/09	Michel Devoret	Yale School of Engineering and Applied Science
Academic	12/2/09	Dirk Bouwmeester	University of California
Academic	21/2/09	Rogerio de Sousa	University of Victoria, Dept of Physics and Astronomy
Academic	22/2/09	Jerome Tribollet	Helmholtz-Zentrum Berlin
Academic	24/2/09	Seth Merkel	University of New Mexico
Academic	27/2/09	Mark Stern	
Academic	2/3/09	Pawel Wocjan	University of Central Florida
Academic	3/3/09	Marcus Silva	Sherbrooke University
Academic	4/3/09	Kenneth G. Paterson	University of London
Academic	4/3/09	Kenneth Patterson	University of London, Royal Holloway, Information Security Group
Academic	7/3/09	Michael Sprague	University of Colorado
Academic	9/3/09	Christopher Monroe	University of Maryland and JQI
Business	12/3/09	Glenn Smith	INO - National Optics Institute
Business	12/3/09	Kevin Tuer	Communitech
Community	13/3/09	Computer Science Undergrad Club	University of Waterloo
Academic	16/3/09	Wolfgang Tittel	University of Calgary
Academic	17/3/09	Jarek Korbicz	Gdansk University of Technology, Poland

Academic	18/3/09	Sabre Kais	Purdue University, Birck Nantechnology Center
Academic	22/3/09	Daniel Nagaj	Slovak Academy of Sciences
Academic	24/3/09	Gabriello Presenza-Pitman	Laurentian University
Academic	25/3/09	Development Officers	University of Waterloo
Academic	25/3/09	Jonathan Ziprick	University of Winnipeg
Academic	26/3/09	Pierre-Luc Dallaire-Demers	Ecole Polytechnique de Montreal
Business	27/3/09	IT Management	Open Text Corporation
Community	27/3/09	Public Lecture-Artist of City Centre Bell	
Academic	30/3/09	Simon Nigg	Universite de Geneve
Academic	31/3/09	Angelo Karantza	University of Toronto
Academic	3/4/09	QIP Class Tour	University of Waterloo
Academic	7/4/09	Akimasa Miyake	Perimeter Institute
Academic	13/4/09	Charles Santori	Hewlett-Packard Laboratories
Business	15/4/09	Board of Governors	Information Technology Association of Canada
Academic	18/4/09	Marco Taucer	McGill University
Business	18/4/09	Staff	Research in Motion
Community	18/4/09	Science Teachers	Science Teachers Association
Academic	20/4/09	Jungsang Kim	Duke University, Electrical and Computer Engineering
Academic	20/4/09	Falk Unger	UC Berkeley
Academic	25/4/09	Vishal Sahni	Dayalbagh Educational Institute
Academic	28/4/09	Jeremie Roland	NEC Labs
Academic	28/4/09	Chunqing Deng	Peking University

49 GROUPS OF VISITORS FROM JANUARY 1ST TO APRIL 30TH, 2009.

Academic	5/3/08	V. Arvind	Faculty, Institute of Mathematical Sciences, Chennai
Academic	5/5/08	Marcos Curty	University of Vigo
Academic	5/12/08	William Matthews	University of Bristol
Academic	5/15/08	Man-Hong Yung	University of Illinois at Urbana-Champaign (UIUC)
Academic	5/15/08	Sir Anthony Leggett	University of Illinois at Urbana-Champaign (UIUC)
Academic	5/21/08	Professor Ian Town	University of Canterbury
Academic	5/22/08	Arthur Carty	University of WAterloo - Nano Technology
Academic	5/25/08	Stephen Bartlett	University of Sydney
Government	5/29/08	Claudia Brillman	Deputy Director, Ministry of Economics, Rheinland-Pfalz State, Germany
Government	5/29/08	Yvonne Denz	Canadian German Chamber of Industry and Commerce
Academic	6/15/08	Yi-Kai Liu	Caltech
Academic	6/15/08	Dervis Can Vural	University of Illinois at Urbana-Champaign (UIUC)
Academic	6/15/08	Guojun Zhu	University of Illinois at Urbana-Champaign (UIUC)
Academic	6/15/08	Daria Ahrensmeier	Trent University
Academic	6/15/08	Shiang Yong Looi	Carnegie Mellon University, Pittsburgh
Academic	6/16/08	Jan Ivar Korsbakken	University of California - Berkeley
Academic	6/16/08	Hirotada Kobayashi	National Institute of Informatics, Japan
Academic	6/16/08	Tsuyoshi Ito	School of Computer Science, McGill University
Business	6/16/08	Third Age Learning Program Committee	
Academic	6/21/08	Alexandre Martins de Souza	Brazilian Center for Research in Physics, Rio de Janeiro, Brazil
Academic	6/23/08	Rene Stock	University of Toronto
Business	6/26/08	New Zealand Delegation	

Academic	7/1/08	Markus Grassl	Institut für Quantenoptik und Quanteninformation (IQOQI)
Academic	7/7/08	Rolando Somma	Perimeter Institute
Academic	7/10/08	Anthony Leverrier	Institut d'Optique Graduate School, France
Academic	7/11/08	Manny Knill	NIST - Mathematical and Computational Sciences Division
Government	7/15/08	Taipei Economic and Cultural Office in Canada	
Academic	7/17/08	Kae Nemoto	National Institute of Informatics, Japan
Academic	7/21/08	Daniel Gottesman	Perimieter Institute Faculty
Academic	7/27/08	Wim van Dam	UC Santa Barbara
Academic	7/29/08	Torsten Franz	Technical University of Braunschweig, Institute for Mathematical Physics
Academic	7/30/08	Volkher Scholz	Technical University of Braunschweig, Institute for Mathematical Physics
Academic	8/4/08	Jagadesh Moodera	MIT - Francis Bitter Magnet Laboratory
Academic	8/11/08	Cecilia Cormick	Universidad de Buenos Aires
Academic	8/17/08	Evan Meyer-Scott	University of Alberta
Academic	8/17/08	Jozef Gruska	Masaryk University, Faculty of Informatics, Czech Republic
Government	8/20/08	Perry Blocher	Ontario Ministry of Research and Innovation
Government	8/20/08	Sandra Watts	Press Secretary to the Minister, John Wilkinson
Academic	8/24/08	Karol Zyczkowski	Jafiellonioan University, Institute of Physics, Poland
Academic	8/24/08	Till J. Weinhold	Griffith University, Centre for Quantum Dynamics, Australia
Academic	8/25/08	Torsten Franz	Technical University of Braunschweig, Institute for Mathematical Physics
Academic	8/26/08	Francesco De Martini	Universita di Roma "La Sapienza"
Academic	8/26/08	Geoff Pryde	Griffith University, Centre for Quantum Computer Technology, Brisbane, Australia

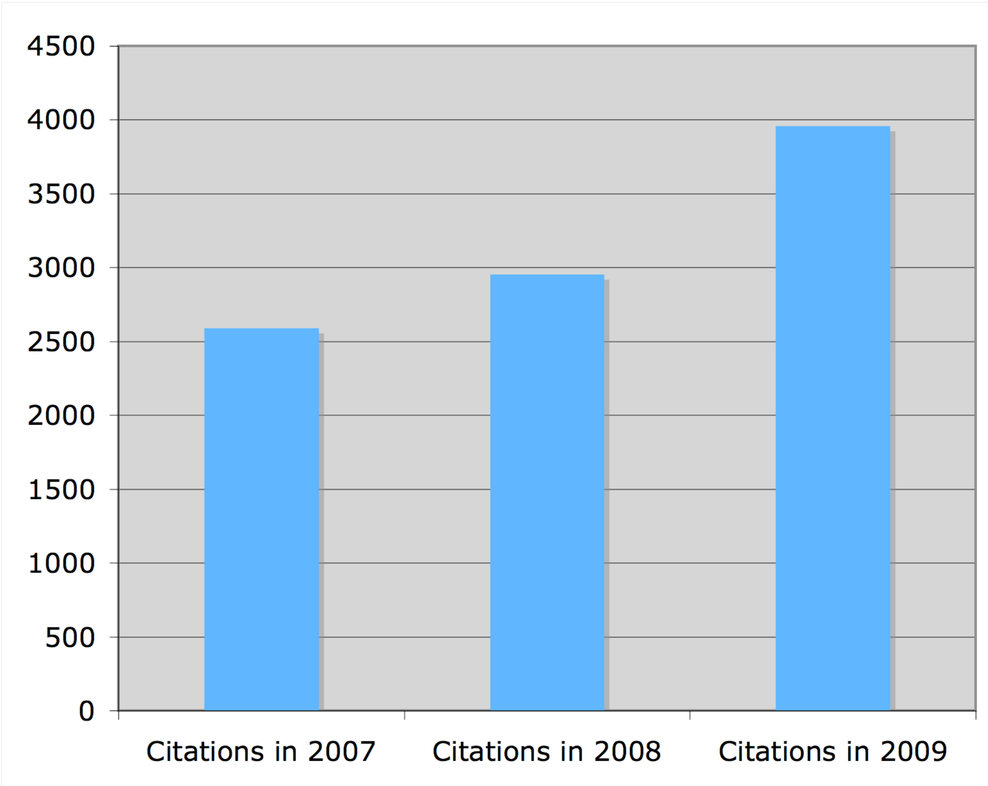
Academic	8/26/08	Brendon Higgins	Griffith University, Centre for Quantum Computer Technology, Brisbane, Australia
Academic	9/4/08	Khaled Mnaymneh	University of St. Andrews, Scotland
Academic	9/6/08	David Hume	National Institute of Standards and Technology, Boulder, CO
Academic	9/12/08	Brian Goddard	McGill
Academic	9/13/08	Thomas Jennewein	IQOQI - Institute for Quantum Optics and Quantum Information
Academic	9/18/08	Lawrence M. Ioannou	University of Cambridge
Academic	9/22/08	Mary Beth Ruskai	Research Professor, Tufts University
Media	9/25/08	Peter Calamai	The Toronto Star, Reporter
Academic	9/29/08	Howard Wiseman	Professor and Federation Fellow, Griffith University, Australia
Business	10/15/08	Simon Labbe	INO - National Optics Institute
Business	10/15/08	Pierre Galarneau	INO - National Optics Institute
Business	10/15/08	Marcia Vernon	INO - National Optics Institute
Business	10/15/08	Glenn Smith	INO - National Optics Institute
Academic	10/20/08	Aaron Denney	University of New Mexico
Government	10/23/08	Ross Hornby	Canadian Ambassador to the European Union
Government	10/23/08	Robin MacNab	Deputy Director (Investment, Science & Technology) Federal Government
Academic	10/24/08	Jacob J. Krich	Harvard University
Government	10/24/08	Mark Scullion	Science and Innovation Counesellor, Canadian Embassy, Tokyo
Government	10/24/08	Chad Fleck	Deputy Director, North Asia Commercial Relations, DFAIT (Ottawa)
Government	10/24/08	Yvonne Grunethaler	Trade Commissioner Science and Innovation, Ontario, DFAIT(Toronto)
Government	10/24/08	Ahmed Hussen	Trade Commissioner Investor Services, DFAIT (Ottawa)

Academic	10/26/08	Mark Saffman	University of Wisconsin, Madison
Academic	10/29/08	Dan Browne	University College London
Academic	11/2/08	Harry Buhrman	Professor - Centrum voor Wiskunde en Informatica (CWI)
Academic	11/5/08	Otfried Guhne	University of Innsbruck
Academic	11/5/08	Richard Slusher	Georgia Tech Quantum Institute
Academic	11/9/08	Jonathan Oppenheim	University of Cambridge
Academic	11/11/08	Richard Hughes	Los Alamos National Laboratory
Academic	11/14/08	Jean-Michel Raimond	Laboratoire Kastler-Brossel, Paris
Business	11/20/08	Dr. Henri Angelino	National Institute of Informatics, Japan
Academic	11/23/08	Alexandre Blais	Université de Sherbrooke
Government	11/24/08	Veenat Rawat	Communications Research Centre Canada
Academic	12/4/08	Aashish Clerk	McGill University
Academic	12/7/08	Ferdinand Schmidt-Kaler	Universität Ulm - Institut für Quanteninformationsverarbeitung
Academic	12/15/08	Andrew Sachrajda	National Research Council Canada
Government	12/18/08	Richard Russell	Office of Science and Technology, Executive Office of the President of the United States
Government	12/18/08	Eric Tsang	Communications Research Centre Canada

124 GROUPS OF VISITORS IN 2008.

Appendix D: Citations

Below is a table with citations/year of papers since 2007 that have been written by IQC members.



Appendix E: Publications

2009:
Journals:

Improving high-T_c dc-SQUID performance by junction asymmetry
Urbasi Sinha, Aninda Sinha, Frank K. Wilhelm
Supercond. Sci. Technol. 22 (2009) 055002
http://arxiv.org/abs/0812.4237

All entangled states are useful for channel discrimination
M. Piani, J. Watrous
arXiv:0901.2118

Broadcast copies reveal the quantumness of correlations
M. Piani, M. Christandl, C. E. Mora, P. Horodecki
arXiv:0901.1280

Coherence Measures for Heralded Single-Photon Sources
E. Bocquillon, C. Couteau, M. Razavi, R. Laflamme, G. Weihs
Phys. Rev. A 79, 035801 (2009)
quant-ph/0807.1725

Demonstration of two-qubit algorithms with a superconducting quantum processor
L. DiCarlo, J. M. Chow, J. M. Gambetta, Lev S. Bishop, D. I. Schuster, J. Majer, A. Blais, L. Frunzio, S. M. Girvin, and R. J. Schoelkopf
arXiv:0903.2030

Dispersive regime of circuit QED: Photon-dependent qubit dephasing and relaxation rates
Maxime Boissonneault, J. M. Gambetta, and Alexandre Blais
Phys. Rev. A 79, 013819 (2009)
arXiv:0810.1336

On the Hitting Times of Quantum Versus Random Walks
Frédéric Magniez, Ashwin Nayak, Peter Richter, and Miklos Santha
Proceedings of the Twentieth Annual ACM-SIAM Symposium on Discrete Algorithms, 2009

Optimal control of a leaking qubit
P. Rebentrost and F.K. Wilhelm
Phys. Rev. B 79, 060507(R) (2009).
arXiv:0808.2680

Optimal control of a qubit coupled to a Non-Markovian Environment
P. Rebentrost, I. Serban, T. Schulte-Herbrueggen, F.K. Wilhelm
Phys. Rev. Lett. 102, 090401 (2009).
quant-ph/0612165

Parametric downconversion and optical quantum gates: two's company, four's a crowd
M. Barbieri, T. J. Weinhold, B. P. Lanyon, A. Gilchrist, K. J. Resch, M. P. Almeida, A. G. White
Journal of Modern Optics, 56, 209 (2009)

Physical and Architectual Considerations in Quantum Repeaters
M. Razavi, K. Thompson, H. Farmanbar, M. Piani, N. Lutkenhaus
SPIE Proc. 7236-2

Proposal for generating and detecting multi-qubit GHZ states in circuit QED
Lev S. Bishop, L. Tornberg, D. Price, E. Ginossar, A. Nunnenkamp, A. A. Houck, J. M. Gambetta, Jens Koch, G. Johansson, S. M. Girvin, and R. J. Schoelkopf
arXiv:0902.0324

Quantum computing using shortcuts through higher dimensions
B. P. Lanyon, M. Barbieri, M. P. Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. J. Pryde, J. L. O'Brien, A. Gilchrist, A. G. White
Nature Physics, 5, 134 (2009)
arXiv:0804.0272

Quantum-optical coherence tomography with classical light
J. Lavoie, R. Kaltenbaek, and K. J. Resch
Optics Express, 17, 3818 (2009)

Randomized benchmarking and process tomography for gate errors in a solid-state qubit
J. M. Chow, J. M. Gambetta, L. Tornberg, Lev S. Bishop, A. A. Houck, B. R. Johnson, L. Frunzio, S. M. Girvin, and R. J. Schoelkopf
Phys. Rev. Lett. 102, 090502 (2009)
0811.4387

Revisiting the critical velocity of a clean one-dimensional superconductor
Tzu-Chieh Wei and Paul M. Goldbart
arXiv:0904.2409

Signatures of nonclassicality in mixed-state quantum computation
Animesh Datta, Sevag Gharibian
PHYSICAL REVIEW A 79, 042325 (2009)

Simple pulses for elimination of leakage in weakly nonlinear qubits
F. Motzoi, J. M. Gambetta, P. Rebentrost, F. K. Wilhelm
arXiv:0901.0534

Spatial entanglement in many body system using quantum walk
Sandeep Goyal and C. M. Chandrashekar
arXiv:0901.0671

Symmetric extension in two-way quantum key distribution
Geir Ove Myhr, Joseph M. Renes, Andrew C. Doherty, Norbert Lütkenhaus
Phys. Rev. A 79, 042329

arXiv:0812.3607

The quantum query complexity of certification
Andris Ambainis, Andrew M. Childs, François Le Gall, and Seiichiro Tani
arXiv:0903.1291

Books & Chapters:

Quantum Computational Complexity
John Watrous
Encyclopedia of Complexity and System Science, Springer, 2009
arXiv:0804.3401

Tutorials:

Spin interactions, relaxation and decoherence in quantum dots
Jan Fischer, Mircea Trif, W. A. Coish, and Daniel Loss
arXiv:0903.0527

2008:
Journals:

A separation between divergence and Holevo information for ensembles
Rahul Jain, Ashwin Nayak, Yi Su
Proceedings of the Theory and Applications of Models of Computation (TAMC) 2008, Mathematical Structures in Computer Science (MSCS) on TAMC 2008.
arXiv:0712.3867v2

A shift in spectroscopy
F.K. Wilhelm
Nature (news and views) 455, 41 (2003)

A spin based heat engine: multiple rounds of algorithmic cooling
C. A. Ryan and O. Moussa and J. Baugh and R. Laflamme
Phys. Rev. Lett. 100, 140401 (2008)
arXiv:0706.2853v2

A theorem about relative entropy of quantum states with an application to privacy in quantum communication
Rahul Jain, Jaikumar Radhakrishnan, Pranab Sen
Journal of ACM (JACM) 2008.
arXiv:0705.2437v1

Amplifying a tiny optical effect
K.J. Resch
Science 319, 733 (2008). (Perspectives)

Beating the channel capacity limit for linear photonic superdense coding
Julio T. Barreiro, Tzu-Chieh Wei, & Paul G. Kwiat

Nature Phys. 4, 282-286 (2008)

Building all Time Evolutions with Rotationally Invariant Hamiltonians
I. Marvian, R.B. Mann
Phys. Rev. A .
quant-ph/0802.0870

Closed timelike curves make quantum and classical computing equivalent
Scott Aaronson and John Watrous
Proceedings of the Royal Society A
arXiv:0808.2669

Comment on "Arbitrated quantum-signature scheme"
Marcos Curty and Norbert Lütkenhaus
Phys. Rev. A 77, 046301 (2008)

Communication in XYZ All-to-All Quantum Networks with a Missing Link
S. Bose, A. Casaccino, S. Mancini, S. Severini
International Journal of Quantum Information
arXiv:0808.0748v1 [quant-ph]

Controlling the spontaneous emission of a superconducting transmon qubit
A. A. Houck, J. A. Schreier, B. R. Johnson, J. M. Chow, Jens Koch, J. M. Gambetta, D. I. Schuster, L. Frunzio, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf
Phys. Rev. Lett. 101, 080502 (2008)
arXiv:0803.4490

Counterexamples to additivity of minimum output p-Renyi entropy for p close to 0
Toby Cubitt, Aram W. Harrow, Debbie Leung, Ashley Montanaro, Andreas Winter
0712.3628v3

Direct Product Theorems for Communication Complexity via Subdistribution Bounds
Rahul Jain, Hartmut Klauck, and Ashwin Nayak
In Proceedings of the Fortieth Annual ACM Symposium on the Theory of Computing, pages 599--608, 2008.

Distinguishing quantum operations with few Kraus operators.
John Watrous
Quantum Information and Computation 8(9): 819–833, 2008

DLCZ quantum repeaters: rate and fidelity analysis
J. Amirloo, M. Razavi, and A. H. Majedi
International Conf. on Quantum Information, Boston, MA, July 2008.

Dynamic nuclear polarization in a double-quantum dot device: electrical induction and detection
J. Baugh, Y. Kitamura, K. Ono, S. Tarucha
Phys. Stat. Sol. (c) 5,(1), 302 (2008)

Effect of detector dead-times on the security evaluation of differential-phase-shift quantum key distribution against sequential attacks
Marcos Curty, Kiyoshi Tamaki, Tobias Moroder
Phys. Rev. A 77, 052321 (2008)
arXiv:0803.1473v1

Emergence of h/e-period oscillations in the critical temperature of small superconducting rings threaded by magnetic flux
Tzu-Chieh Wei and Paul M. Goldbart
Phys. Rev. B 77, 224512 (2008)

Entangled Quantum Key Distribution Over Two Free-Space Optical Links
C. Erven and C. Couteau and R. Laflamme and G. Weihs
Opt. Exp. 16, 16840 (2008)
arXiv:0807.2289

Entanglement Based Free-Space Quantum Key Distribution
C. Erven and C. Couteau and R. Laflamme and G. Weihs
Proc. SPIE 7099, 709916 (2008)

Entanglement-redistribution boxes
Andrzej Grudka, Michal Horodecki, Pawel Horodecki, Ryszard Horodecki, and Marco Piani
Phys. Rev. A 78, 042317 (2008)
arXiv:0807.3811

Epsilon-measures of entanglement
Caterina Mora, Marco Piani, Hans Briegel
New J. Phys. 10, 083027 (2008)
arXiv:0802.4051v1

Experimental quantum key distribution with an untrusted source
X. Peng, H. Jiang, B. Xu, X. Ma, and H. Guo
Optics Letters, Vol. 33, Issue 18, pp. 2077-2079
0806.1671v2

Exponential decay in a spin bath
W. A. Coish, Jan Fischer, and Daniel Loss
Phys. Rev. B 77, 125329 (2008)
arXiv:0710.3762

Filling a cavity with photons and watching them leave
Alexandre Blais and Jay M. Gambetta
Physics 1, 39 (2008)

Frame representations of quantum mechanics and the necessity of negativity in quasi-probability representations
C. Ferrie and J. Emerson
J. Phys. A: Math. Theor. 41, 352001 (2008)

Generic quantum walk using a coin-embedded shift operator
C.M. Chandrashekar
Phys. Rev. A, 78, 052309 (2008)
arXiv : 0810.1556

Growth and Characterization of GaAs Nanowires on Carbon Nanotube Composite Films: Toward Flexible Nanodevices
Parsian K. Mohseni, Gregor Lawson, Christophe Couteau, Gregor Weihs, Alex Adronov and Ray R. LaPierre
Nano Lett., 2008, 8 (11), pp 4075–4080

Inverse H-C *ex situ* HRMAS NMR Experiments for Solid-Phase Peptide Synthesis
T.R. Ramadhar, F. Amador, M.J.T. Ditty, W.P. Power
Magn. Reson. Chem. 46(1), 30, 2008, DOI: 10.1002/mrc.2118 .

Iterations of nonlinear entanglement witnesses
T. Moroder, O. Gühne, N. Lütkenhaus
Phys. Rev. A 78, 032326 (2008)
arXiv:0806.0855v1

Lieb-Robinson bounds and the speed of light from topological order
A. Hamma, F. Markopoulou, I. Premont-Schwarz, S. Severini
Phys. Rev. Lett.
arXiv:0808.2495v1

Long-distance quantum communication with multiple quantum memories
Mohsen Razavi, Jeffrey H. Shapiro
Technical Digest, Paper JWA48, San Diego, CA, Feb. 2008

Long-range coupling and scalable architecture for superconducting ux qubits
Austin G. Fowler, William F. Thompson, Zhizhong Yan, Ashley M. Stephens and Frank K. Wilhelm
Can. J. Phys. 86, 533 (2008).

Magnetic and Electrical Control of Electron-Nuclear Spin Coupling in GaAs Double Quantum Dots
Seigo Tarucha and Jonathan Baugh
Journal of the Physical Society of Japan 77, 031011 (2008)

Manipulating biphotonic qutrits
B. P. Lanyon, T. J. Weinhold, N. K. Langford, J. L. O'Brien, K. J. Resch, A. Gilchrist, and A. G. White
Phys. Rev. Lett. 100, 060504 (2008).
arXiv:0707.2880

Model for monitoring of a charge qubit using a radio-frequency quantum point contact including experimental imperfections
Neil P. Oxtoby, Jay Gambetta, and H. M. Wiseman
Phys. Rev. B 77, 125304 (2008)

Multiple Quantum Well AlGaAs Nanowires
C. Chen, N. Braidy, C. Couteau, C. Fradin, G. Weihs, R. LaPierre
Nano. Lett. 8, 495 (2008).
arXiv:0803.0881

New binding-concealing trade-offs for quantum string commitment
Rahul Jain
Journal of Cryptology (JoC), 2008.
arXiv:quant-ph/0506001v4

Non-locality and communication complexity
H. Buhrman, R. Cleve, S. Massar, and R. de Wolf
Submitted to Reviews of Modern Physics (2008)

Nonclassicality without entanglement enables bit commitment
Howard Barnum, Oscar C.O. Dahlsten, Matthew Leifer, Ben Toner
Proc. IEEE Workshop on Information Theory 2008
arXiv:0803.1264v1

Nonequilibrium transport in mesoscopic multi-terminal SNS Josephson junctions
M.S. Crosser, Jian Huang, F. Pierre, Pauli Virtanen, Tero T. Heikkilä, F. K. Wilhelm, Norman O. Birge
Phys. Rev. B 77, 014528 (2008).
arXiv:0801.1324

Nonlinear dispersive regime of cavity QED: The dressed dephasing model
Maxime Boissonneault, J. M. Gambetta, and Alexandre Blais
Phys. Rev. A 77, 060305(R) (2008)
arXiv:0803.0311

Nuclear spin dynamics and Zeno effect in quantum dots and defect centers
D. Klauser, W. A. Coish, and Daniel Loss
Phys. Rev. B 78, 205301 (2008)
arXiv:0802.2463v1 [cond-mat.mes-hall]

On Transmission line resonances in High Tc dc SQUIDs
Urbasi Sinha, Aninda Sinha and Edward Tarte
Supercond. Sci. Technol. 21 (2008) 085021.
arXiv:0806.3187

Optimizing the discrete time quantum walk using a SU(2) coin
C. M. Chandrashekar, R. Srikanth, and Raymond Laflamme
Phys. Rev. A 77, 032326 (2008)
arXiv:0711.1882

Optoelectronic Characterization of Fiber-Coupled NbN Superconducting Nanowire Single Photon Detector
Zhizhong Yan; M. K. Akhlaghi; JL. Orgiazzi; A. Hamed Majedi
accepted for publication in *Journal of Modern Optics*

Pure-state quantum trajectories for general non-Markovian systems do not exist
Howard M. Wiseman and J. M. Gambetta
Phys. Rev. Lett. 101, 140401 (2008)
arXiv:0806.3101

Quantum Algorithm for Checking Matrix Identities
Ashwin Nayak
Encyclopedia of Algorithms 2008

Quantum Circuit Placement
D. Maslov, S. M. Falconer, and M. Mosca
IEEE Transactions on CAD 27(4):752-763, April 2008
arXiv:quant-ph/0703256

Quantum Circuit Simplification and Level Compaction
D. Maslov, G. W. Dueck, D. M. Miller, and C. Negrevergne
IEEE Transactions on CAD, 27(3):436-444, March 2008

Quantum computing using shortcuts through higher dimensions
B. P. Lanyon, M. Barbieri, M. P. Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. J. Pryde, J. L. O'Brien, A. Gilchrist, A. G. White
Nature Physics, Advance Online Publication 2008
arXiv:0804.0272

Quantum Graphity: a model of emergent locality
Tomasz Konopka, Fotini Markopoulou, Simone Severini
Accepted for publication in Phys. Rev. D.
arXiv:0801.0861v1 [hep-th]

Quantum nondemolition-like fast measurement scheme for a superconducting qubit
I. Serban, B.L.T. Plourde and F.K. Wilhelm
Phys. Rev. B 78, 054507 (2008)
arXiv:0803.0958

Quantum oscillations in the spin-boson model: Reduced visibility
Frank Wilhelm
New J. Phys. 10, 115011 (2008).

Quantum phase transition using quantum walks in an optical lattice
C. M. Chandrashekar and Raymond Laflamme
Phys. Rev. A 78, 022314 (2008)
arXiv:0709.1986

Quantum Reference Frames and the Classification of Rotationally-Invariant Maps
J.-C. Boileau, L. Sheridan, M. Laforest, S. D. Bartlett
J. Math. Phys. 49, 032105 (2008)
arXiv:0709.0142

Quantum Repeaters using Coherent-State Communication

P. van Loock, N. Lütkenhaus, W. J. Munro, K. Nemoto
Phys. Rev. A 78, 062319 (2008)
arXiv:0806.1153v1

Quantum trajectory approach to circuit QED: Quantum jumps and the Zeno effect
Jay Gambetta, Alexandre Blais, M. Boissonneault, A. A. Houck, D. I. Schuster, and S. M. Girvin
Phys. Rev. A 77, 012112 (2008)

Quantum-inspired interferometry with chirped laser pulses
R. Kaltenbaek, J. Lavoie, D. N. Biggerstaff, K. J. Resch
Nature Physics 4, 828 (2008)
arXiv:0804.4022

Quantumness Witnesses
R. Alicki, M. Piani, and N. Van Ryn
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Randomized benchmarking and process tomography for gate errors in a solid-state qubit
J. M. Chow, J. M. Gambetta, L. Tornberg, Lev S. Bishop, A. A. Houck, B. R. Johnson, L. Frunzio, S. M. Girvin, and R. J. Schoelkopf
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Relative entropy of entanglement for certain multipartite mixed states
Tzu-Chieh Wei
Phys. Rev. A 78, 012327 (2008)
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Scalable Experimental Protocol for Identification of Correctable Codes
M. Silva, E. Magesan, D. Kribs, and J. Emerson
Phys. Rev. A. 78, 012347 (2008)

Space-QUEST: Experiments with quantum entanglement in space
Rupert Ursin, Thomas Jennewein, Johannes Kofler, Josep M. Perdigues, Luigi Cacciapuoti, Clovis J. de Matos, Markus Aspelmeyer, Alejandra Valencia, Thomas Scheidl, Alessandro Fedrizzi, Antonio Acin, Cesare Barbieri, Giuseppe Bianco, Caslav Brukner, Jose Capmany, Sergio Cova, Dirk Giggenbach, Walter Leeb, Robert H. Hadfield, Raymond Laflamme, Norbert Lutkenhaus, Gerard Milburn, Momtchil Peev, Timothy Ralph, John Rarity, Renato Renner, Etienne Samain, Nikolaos Solomos, Wolfgang Tittel, Juan P. Torres, Morio Toyoshima, Arturo Ortigosa-Blanch, Valerio Pruneri, Paolo Villoresi, Ian Walmsley, Gregor Weihs, Harald Weinfurter, Marek Zukowski, Anton Zeilinger
IAC Proceedings A2.1.3 (2008)
arXiv:0806.0945v1

Spin decoherence of a heavy hole coupled to nuclear spins in a quantum dot
Jan Fischer, W. A. Coish, D. V. Bulaev, and Daniel Loss
Phys. Rev. B 78, 155329 (2008)

arXiv:0807.0386

Squashing Models for Optical Measurements in Quantum Communication
Normand J. Beaudry, Tobias Moroder, Norbert Lütkenhaus
Phys. Rev. Lett. 101, 093601 (2008)
arXiv:0804.3082v3

Superconductive Traveling-Wave Photodetectors: Fundamentals and Optical Propagation
B. G. Ghamsari, and A. H. Majedi
IEEE J. Quantum Electron., vol. 44, no. 7, pp 667-675, July 2008.

Suppressing charge noise decoherence in superconducting charge qubits
J. A. Schreier, A. A. Houck, Jens Koch, D. I. Schuster, B. R. Johnson, J. M. Chow, J. M. Gambetta, J. Majer, L. Frunzio, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf
Phys. Rev. B 77, 180502(R) (2008)
arXiv:0712.3581

Symmetrization Methods for Characterization and Benchmarking of Quantum Processes
J. Emerson
Can. J. Phys. 86(4): 557-561 (2008)

Symmetry-noise interplay in quantum walk on an n-cycle
Subhashish Banerjee, R. Srikanth, C.M. Chandrashekar, and Pranaw Rungta
Phys. Rev. A, 78, 052316 (2008)
arXiv:0803.4453

Testing Born's Rule in Quantum Mechanics with a Triple Slit Experiment
Urbasi Sinha, Christophe Couteau, Zachari Medendorp, Immo Söllner, Raymond Laflamme, Rafael Sorkin and Gregor Weihs
Submitted to the proceedings of Foundations of Probability and Physics-5, Vaxjo, Sweden, August 2008.
arXiv: 0811.2068

Testing quantum devices: Practical entanglement verification in bipartite optical systems
Hauke Haseler, Tobias Moroder, Norbert Lutkenhaus
Phys. Rev. A 77, 032303
arXiv:quant-ph/0711.2709

The GHZ state in secret sharing and entanglement simulation
Anne Broadbent, Paul Robert Chouha and Alain Tapp.
Proceedings of the Third International Conference on Quantum, Nano and Micro Technologies
arXiv:0810.0259

The Quantum Locker Puzzle
David Avis and Anne Broadbent
Proceedings of the Third International Conference on Quantum, Nano and Micro Technologies
arXiv:0812.2242

THz Transmission Lines based on Surface Waves in Plasmonic Waveguides
B. G. Ghamsari, and A. H. Majedi
J. Appl. Phys., 104, 083108, (2008)

Towards a world with quantum computers
D. Bacon, D. Leung
Comm. ACM, 50(9), 55 (2008)

Two-resonator circuit quantum electrodynamics: A superconducting quantum switch
M. Mariantoni, F. Deppe, A. Marx, R. Gross, F.K. Wilhelm, and E. Solano
Phys. Rev. B 78, 104508 (2008).

Weighing matrices and optical quantum computing
S. Flammia, S. Severini
Journal of Physics A: Math. Theor.
arXiv:0808.2057v1 [quant-ph]

Books & Chapters:

A Separation between Divergence and Holevo Information for Ensembles
R. Jain, A. Nayak, Y. Su
Proceedings of the 5h Annual Conference on Theory and Applications of Models of Computation, Vol. 4978, 2008

An Introduction to Quantum Computing
P. Kaye, R. Laflamme, M. Mosca
Oxford University Press, (ISBN: 0198570007)

Aspect Experiment
A.J. Leggett
A Compendium of Quantum Physics, eds. F.Weinert,D.Greenberger,B. Falkenburg and K.Hentschel, Springer-Verlag 2008

Bell's Theorem
A.J. Leggett
A Compendium of Quantum Physics, eds. F.Weinert,D.Greenberger,B. Falkenburg and K.Hentschel, Springer-Verlag 2008

Bose-Einstein Condensation
A.J. Leggett
A Compendium of Quantum Physics, eds. F.Weinert,D.Greenberger,B. Falkenburg and K.Hentschel, Springer-Verlag 2008

Delayed-choice Experiments
A.J. Leggett
A Compendium of Quantum Physics, eds. F.Weinert,D.Greenberger,B. Falkenburg and K.Hentschel, Springer-Verlag 2008

Direct Product Theorems for Communication Complexity via Subdistribution Bounds

R. Jain, H. Klauck, A. Nayak
Proceedings of the 40th ACM Symposium on the Theory of Computing

Quantum algorithms for evaluating min-max trees
R. Cleve, D. Gavinsky, and D. L. Yonge-Mallo
In Y. Kawano and M. Mosca (Eds.), TQC 2008, LNCS 5106, pp. 11–15 (2008)
quant-ph/0710.5794

Tutorials:

Quantum algorithms for algebraic problems
A. M. Childs and W. van Dam
To appear in Reviews of Modern Physics
arXiv:0812.0380

Superconducting Qubits
John Clarke and Frank K. Wilhelm
Nature Insight 453, 1031 (2008).

Appendix F: Courses

Courses in quantum information have been offered at UW since the 1999-2000 academic year, with the number and breadth of courses increasing substantially in recent years. We offer an introduction to quantum information processing at the undergraduate (CO481/CS467/PHYS467) and graduate (CO681/CS667/PHYS767) levels, as well as many other advanced courses specializing in various aspects of quantum information. These courses can be taken as part of a wide range of graduate and undergraduate programs offered at UW. Below is a list of quantum information courses taught by IQC Faculty since 2008.

Future Courses
2009
- Introduction to Quantum Information & Control in Physical Systems (winter 2010)
- Introduction to Quantum Information Processing (winter 2010)

Current Courses
2009
- Topics in Quantum Information (spring 2009)

Previous Courses
2009
- Sir Anthony Leggett Lecture Series (summer 2009)
- Theory of Open Quantum Systems (winter 2009)
- Selected Topics in Theoretical Physics: Entanglement Theory (winter 2009)
- Introduction to Quantum Information Processing (winter 2009)

Previous Courses
2008
- Theory of Quantum Information (fall 2008)
- Introduction to Quantum Information Processing (fall 2008)
- Introduction to Quantum Information Processing (winter 2008)
- Quantum Electronics and Photonics (winter 2008)
- Quantum Algorithms (winter 2008)
- Sir Anthony Leggett Lecture Series 2008
- Topics in Quantum Information Quantum Information Theory, Error-correction, and Cryptography (spring 2008)

Appendix G: Upcoming Conferences

4th Workshop on Theory of Quantum Computation, Communication and Cryptography (TQC) May 11-13, 2009
www.iqc.ca/tqc2009
Quantum computation, quantum communication, and quantum cryptography are subfields of quantum information processing, an interdisciplinary field of information science and quantum mechanics. TQC 2009 focuses on theoretical aspects of these subfields. The objective of the workshop is to bring together researchers so that they can interact with each other and share problems and recent discoveries. The workshop will be held May 11-13, 2009, at the University of Waterloo. It will consist of invited talks, contributed talks, and a poster session.

The scope of the workshop includes, but is not limited to:

- Quantum algorithms
- Models of quantum computation
- Quantum complexity theory
- Simulation of quantum systems
- Quantum cryptography
- Quantum communication
- Quantum estimation and measurement
- Quantum noise
- Quantum coding theory
- Fault-Tolerant quantum computing
- Entanglement theory

Invited speakers include:

- Masato Koashi (Osaka University)
- John Preskill (Caltech)
- Miklos Santha (Université Paris Sud)
- Graeme Smith (IBM Watson)
- Stephanie Wehner (Caltech)

Undergraduate School on Experimental Quantum Information Processing (USEQIP) June 1-12, 2009
www.iqc.ca/conferences/useqip
A two-week program on the theory and experimental study of quantum information processors aimed primarily at students just completing their junior year. The program is designed to introduce students to the field of quantum information processing. The lectures are geared to students of engineering, physics, chemistry and math, though all interested students are invited to apply. The program has space for eight students and is fully funded through the Institute for Quantum Computing. All travel and housing costs are funded.

The summer school is staffed by the faculty of the Institute for Quantum Computing, a multidisciplinary research center at the University of Waterloo and an internationally recognized leader in the development of quantum information processors. The two-week program will consist of lectures introducing quantum information theory and experimental approaches to quantum devices, followed by hands-on exploration of QIP using the experimental facilities of the institute.

The program will include:

- Introduction to quantum information processing, including a brief review of quantum mechanics and linear algebra
- Introduction to nuclear magnetic resonance, which is a versatile test-bed for QIP and will be used to experimentally explore QIP concepts
- Introduction to optics, Mach-Zender interferometry and Bell inequalities
- Introduction to quantum cryptography
- Introduction to quantum error correction
- Introduction to quantum algorithms
- Introduction to current questions in foundations of quantum mechanics including quantum measurement

Quantum Cryptography School for Young Students (QCSYS) July 27-31, 2009
www.iqc.ca/qcsys
QCSYS is an exciting week-long program offered to Canadian students in Grades 10-12. The program is run by the Institute for Quantum Computing in conjunction with the University of Waterloo.

Students will be given a first-hand look into one of the most exciting topics in modern science – quantum cryptography. Not only will students have the opportunity to be exposed to cutting-edge topics like quantum physics and cryptography, they will have the opportunity to meet some of the most renowned researchers the field has to offer. In addition, students will get a tour of quantum computing and quantum cryptography experiments.

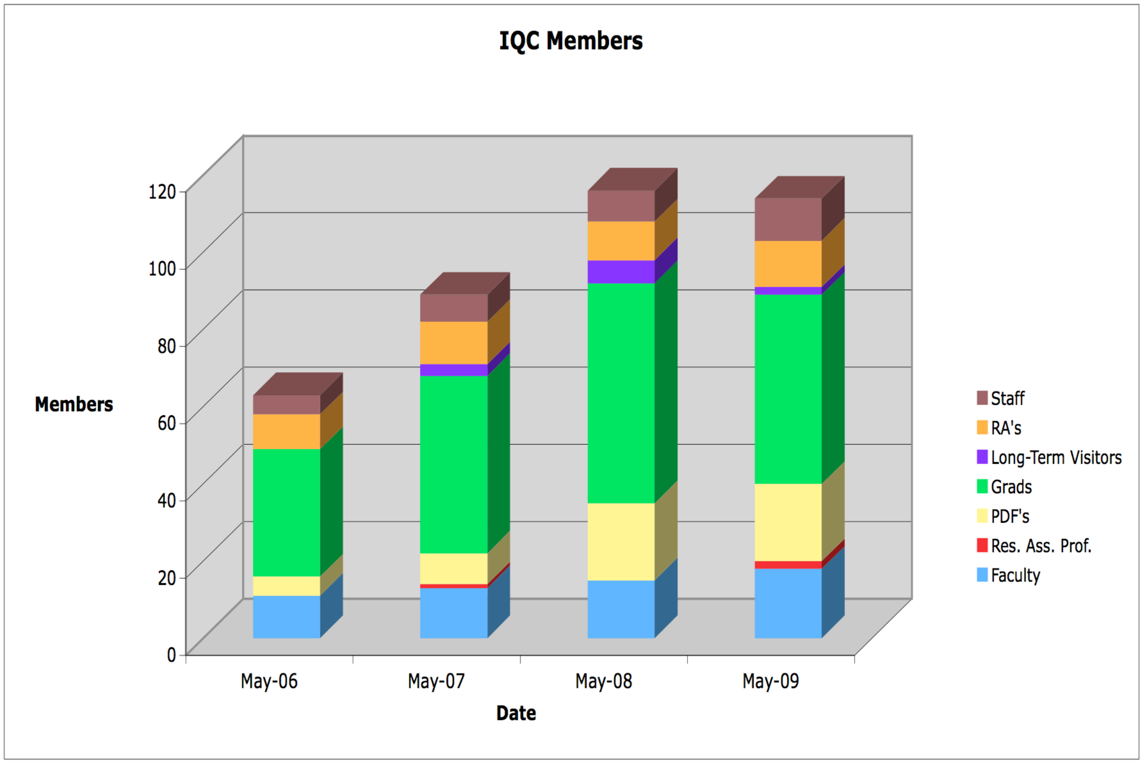
The majority of enrollments will be reserved for Grade 11 students, however this year the program is open to accepting a small number of Grade 10 and Grade 12 applicants.

Mathematics in Experimental Quantum Information Processing Workshop
August 10-14, 2009
The Mathematics in Experimental Quantum Information Processing Workshop is in collaboration with the Fields Institute in Toronto. This meeting aims to review recent progress in using a variety of mathematical techniques that have helped understand the latest generation of quantum information experiment and strengthen the interaction between theorists and experimentalists.

Appendix H: IQC's Team

IQC currently has 18 faculty, 20 pdfs, 65 grad and undergrad students and 13 staff. In the next year, IQC will grow to 20 faculty, 27 pdfs, and 32 research assistants. The figure below gives a current view of IQC.

The following graph shows increases of IQC members per various categories; Faculty, Research Professors, PDFs, Graduate students, Long-term visitors, Research Assistants (undergraduate students) and Staff.



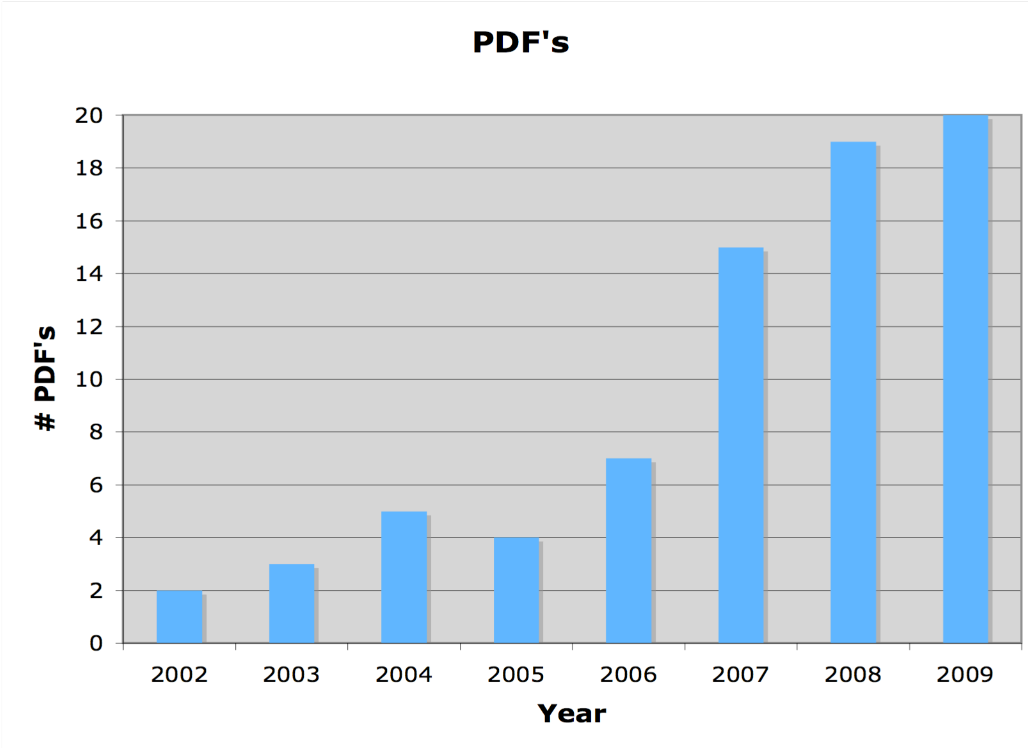
The adjacent figure shows the different areas of expertise of IQC members and where we plan to hire in the future (with AA: A Ambainis; JB:J Baugh; AC: AN AChilds; RC: R Cleve; JE: J Emerson; RL: R Laflamme; DL: D Leung; NL: N Lutkenhaus; HM: H Majedi; MM: M Mosca; AN A Nayak; KR K Resch; JW J Watrous; GW: G Weihs; FW: F Wilhelm, BR: B Reichardt, AL: A Lupascu, TJ: T. Jennewein, TBH: to be hired). Amongst the target hires, we are presently in negotiations with a senior experimental physicist at a top American University.

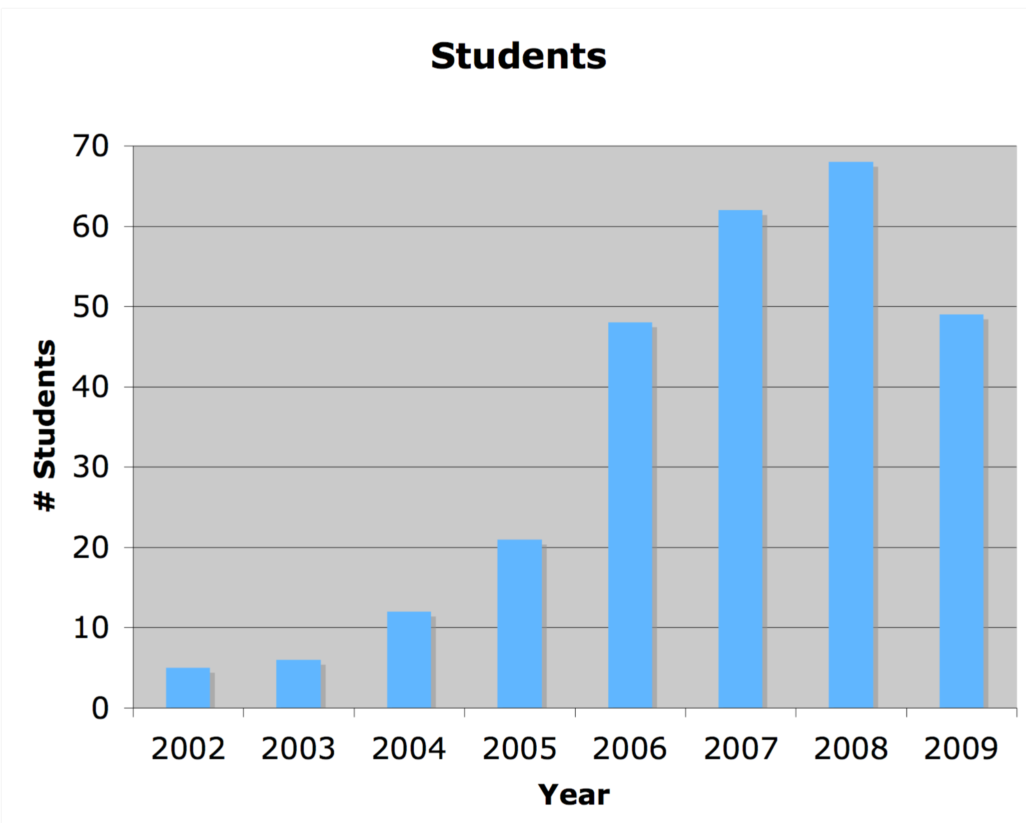
			AA	JB	AC	RC	JE	RL	DL	NL	HM	MM	AN	KR	JW	GW	FW	BR	AL	TJ	TBH
Theory	Q. Info																				1
	Q. Algorithms		x		x	x		x				x	x		x			x			
	Q. Error Correction							x										x			
	Q. Complexity		x					x					x		x						
	Q. Communication					x			x	x											1
	Q. Control																x				1
	Q. Cryptography								x	x		x					x				
	Q.Metrology				x							x									
	Physics																x				1
Expts	Spins	nuclear						x													
		electronic		x																	
	Superconducting																		x		1
	Q. Dots																				2
	Atomic: ion trap																				1
	Photonic																				
		source												x		x				x	
		detectors									x										
		free space						x								x				x	
		fiber																			1
	Q. Repeaters																				1
	Material Science																				2
Total																					12

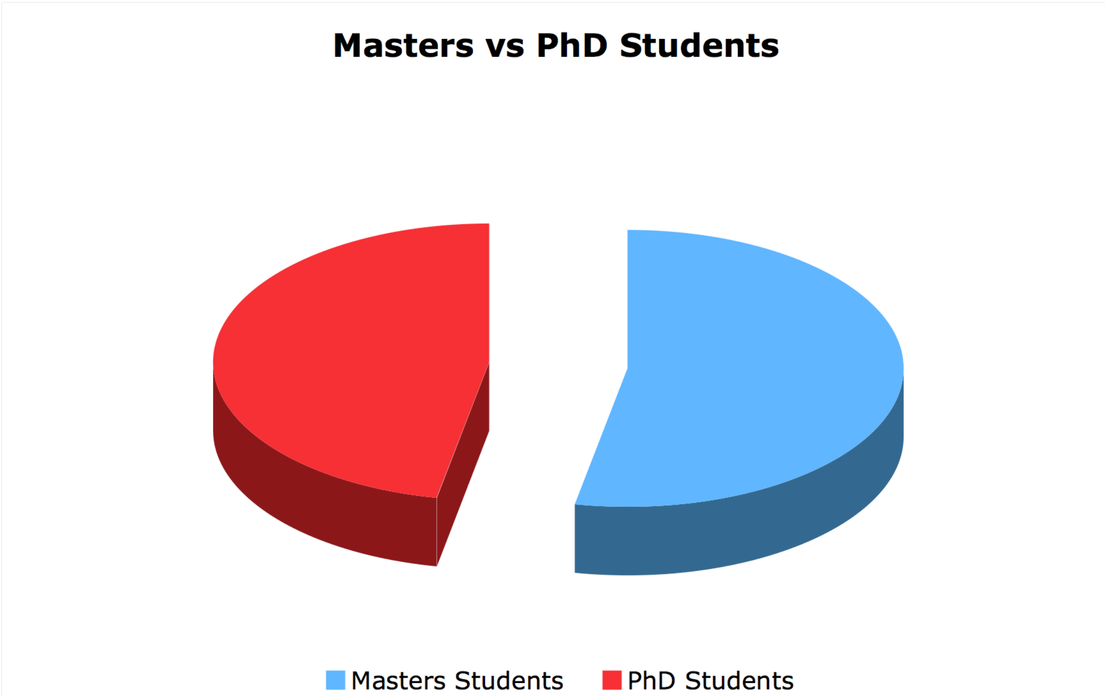
The hiring plan for the years to come is as follows:

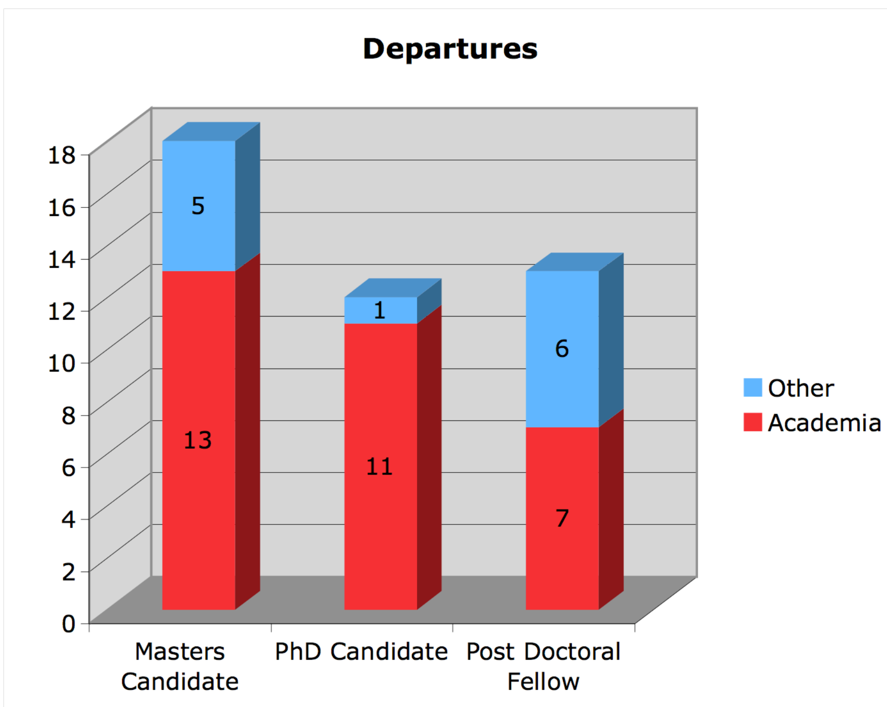
	Year08/09	year09/10	year10/11	year11/12	year12/13	year13/14
# of Faculty	18	20	21	23	26	30

PDFs and Students







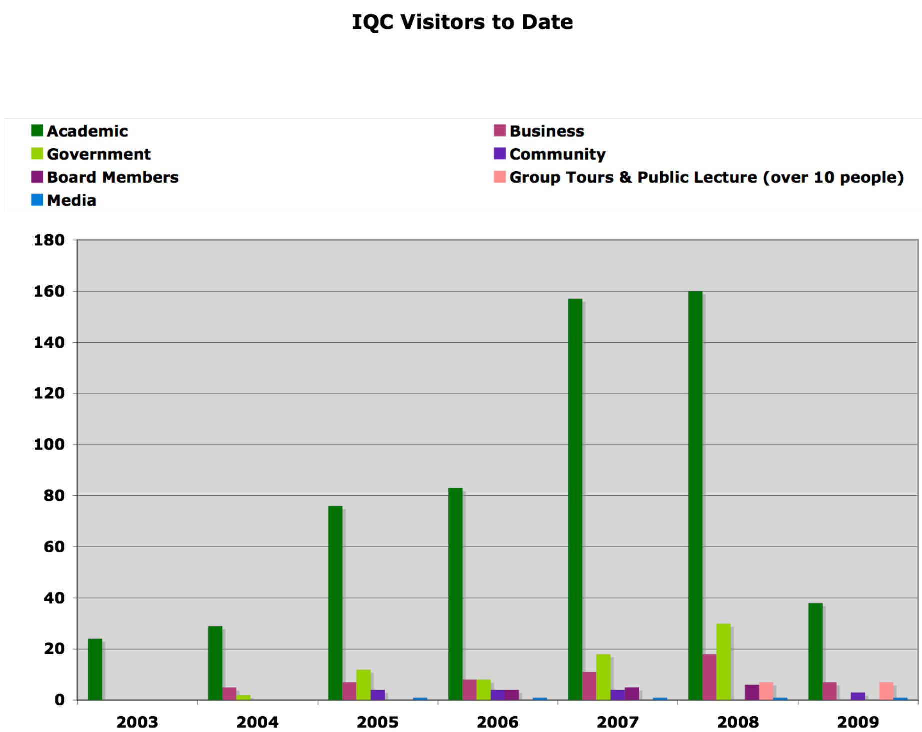


Since the inception of IQC 18 Masters students and 12 PhDs have graduated and 13 Postdoctoral Fellows have moved on. The above diagram depicts how many of each has moved to academic and other positions.

Appendix I: Research, Teaching and Outreach Activities

To complement the research that has been done at IQC, we have also organized meetings, workshops, courses, outreach activities and conferences in the last two years. Some of them are highly specialized, such as ones on security proofs in quantum cryptography and others are more general such as public lectures.

Alongside these activities, there is a strong visitor program, which has brought more than 700 visitors since the inception of IQC; you can find a list of visitors since 2008 in Appendix C. These visitors include researchers, students and teachers, business partners, journalists and members of government agencies.



*Note: the 2009 visitor statistics only represent those up until April 30th, 2009.

From Winter 2008 to Winter 2009 another 10 semester courses in various aspects of quantum information have been taught, including the introduction of new courses. In addition, Sir Tony Leggett, the Mike and Ophelia Lazaridis visiting professor will teach his 4th annual lecture series on quantum information.

The core course "Introduction to Quantum Information Processing" was split into separate graduate and undergraduate sections due to overwhelming demand.

We now have a sufficient base of courses in quantum information to launch a strong graduate program. We are developing more detailed plans to launch a graduate program in quantum information at IQC, and will also introduce additional opportunities to engage students at the undergraduate and high school level. This will include new Masters and PhD programs focusing on quantum information, with the opportunity for various specializations. Refer to Page 17 for more information.

Looking ahead to Winter 2010, two more courses are scheduled to be taught. Jonathan Baugh is teaching "Introduction to Quantum Information and Quantum Control in Physical Systems", and Andrew Childs will be teaching the "Introduction to Quantum Information Processing" course. A detailed list of courses taught is given in Appendix F.

IQC will organize a series of events in Waterloo to communicate and disseminate to the research community, to industry/government partners and to the public in general the results of the research carried out at IQC and its importance for the future. Example of events includes tours for visitors, scientific conferences and outreach activities that will help recruit the best and brightest students. These interested tour groups are curious to find out what kind of research is being done and to get a first-hand look at IQC's laboratories and experiments. Since January 2009, IQC is averaging one tour every two weeks. These tours have created opportunities to collaborate and share information with those who have a similar interest in our research areas.

Conferences, Workshops & Schools
The first conference planned is the 4th Workshop on Theory of Quantum Computation, Communication and Cryptography that ran from May 11-13th. The objective of the workshop is to bring researchers together for the purpose of interaction and sharing of problems and recent discoveries.

A summer school for undergraduate students consisting of a two-week program on the theory and experimental study of quantum information processors is aimed primarily at students just completing their junior year. The program is set to begin in June and is designed to introduce students to the field of quantum information processing. The lectures are geared to students of engineering, physics, chemistry and math, though all interested students are invited to apply. This year, a pilot project, the program has space for a dozen.

The Quantum Cryptography School for Young Students (QCSYS) is an exciting week-long program in July offered to Canadian students in Grades 10-12. Students will be given a first-hand look into one of the most exciting topics in modern science-quantum cryptography. Not only will students have the opportunity to be exposed to cutting-edge topics like quantum physics and cryptography - they will have the opportunity to meet some of the most renowned researchers the field has to offer. In addition, students will get a tour of quantum computing and quantum cryptography experiments.

Finally, this coming August, we will be hosting the Mathematics in Experimental Quantum Information Processing Workshop in collaboration with the Fields Institute in Toronto, scheduled for this coming August. This meeting aims to review recent progress in using a variety of mathematical techniques that have helped us to understand the latest generation of quantum information experiment and strengthen the interaction between theorists and experimentalists.

For more detailed information, please see Appendix G.

Appendix J: National Leadership & International Status

Canada has two main research networks in quantum information, one through the Canadian Institute for Advanced Research (CIFAR) and the other an Innovation Platform from NSERC.

CIFAR QIP program

The Canadian Institute for Advanced Research (CIFAR, www2.cifar.ca), is a public-private research organization that enables top-tier researchers to collaborate on groundbreaking advanced research. CIFAR's Quantum Information Processing (QIP) program, led by Dr Laflamme since its 2002 inception, focuses on fundamental issues in quantum information, emphasizing high risk but potentially high payoff investigations. The program was renewed in 2007 for another 5 years. The reviewers' report for the successful renewal of the program says: "…Immediately upon the consequent founding of the Perimeter Institute and the Institute for Quantum Computing (IQC), steady stream of top theoretical talent began arriving in Canada from many places throughout the world. As a result, at present Canada has a commanding position in almost all theoretical areas of quantum information science; it can with fairness be considered number one in the world, by many measures, in many subspecialties of this field."

The program has meetings twice a year where IQC faculty and the rest of the Canadian and international communities exchange information and collaborate informally in a variety of projects.

QuantumWorks

QuantumWorks is a NSERC Innovation Platform launched in June 2006 as an administrative sub-group in the IQC. QuantumWorks was originally granted $5M over its five-year mandate (2006-2011). Since its launch, QuantumWorks funding has been increased to $6M (see "QWIPEI" below). It brings together various stakeholders on the national level, and also acts as a gateway to Canada's quantum information community for groups around the world. Dr. Laflamme serves as Scientific Director of QuantumWorks. QuantumWorks draws members from eight institutions across Canada and the IQC contributes almost half of QuantumWorks' membership (20 of 40 members, including Associate Members), by far the largest contribution of personnel in the network. As it carries out its mandate, QuantumWorks is another avenue in which the IQC increases its stature within Canada as well as across the globe.

QuantumWorks is the first organization in Canada to bring together quantum information processing expertise from across the country. This field is an area of rapid growth, and a mechanism to respond to this growth was needed. To that end, NSERC awarded the QuantumWorks Innovation Platform Enhancement Initiative (QWIPEI) in September 2007. The additional $1M in funding represents a 25 per cent increase in the QuantumWorks budget over the final four years of its mandate (2007-2011). The majority of the QWIPEI funding is earmarked to support the research of new members. With additional funding from the QWIPEI, six new researchers were inducted into QuantumWorks. These six were chosen on the quality of their research and potential for future collaborations. Three (3) of the six new members are affiliated with the IQC.

QuantumWorks holds an Annual General Meeting & Technical Conference each year. Each event has had approximately 100 attendees. All participants, including speakers, have been drawn from faculty; graduate students; postdoctoral fellows and stakeholders from industry, academia and government institutions. The format follows that of a traditional scientific conference, but with generous amounts of time for discussions. As a direct result of these events, existing collaborations have been strengthened and new relationships have been forged. One set of particularly valuable interactions is that between grad students and non-academic participants. These interactions offer young scientists a unique perspective on their work.

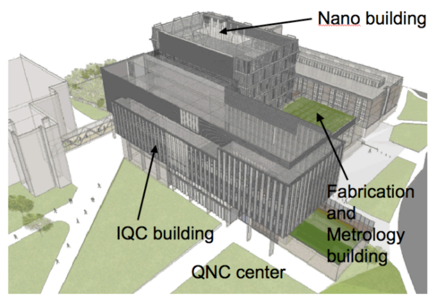
QuantumWorks also sponsors events organized by its members. QuantumWorks has given or allocated $97,900 in support of these events with $62,300 going to events organized by IQC members, a rate of almost 64 per cent.

The quantum information community in Canada is growing quickly, and hubs of activity are developing independently. QuantumWorks is working to keep the Canadian research community in close communication even as that community grows by creating an Associate Member status. Associate Members have to be nominated by current members of QuantumWorks and display either ongoing collaboration or the potential for collaboration in the future. Of the first 10 Associate Member applicants, 7 are associated with the IQC. These membership numbers has risen from 42 per cent in 2006 to 50 per cent in 2009.

As the national network for quantum information research, QuantumWorks has played an important role in linking IQC personnel with national and international stakeholders.
Within Canada, QuantumWorks served as the contact point for three different projects totaling $75,000 with the Communications Security Establishment Canada (CSEC). The CSEC is also preparing to take advantage of QuantumWorks' internship program to have a student from the IQC work with CSEC researchers on-site. Internationally, QuantumWorks has acted as the administrative portal for IQC faculty member Norbert Lütkenhaus to lead a Canadian contingent in an Industry Specification Group on Quantum Key Distribution set up by the European Telecommunications Standards Institute (ETSI). Also associated with this Specification Group is a Specialist Task Force for researchers with particular expertise on specific issues relevant to the Specification Group. Prof. Lütkenhaus has also taken on the role of QuantumWorks' key technical person for the task force.

Appendix K: IQC Building

IQC currently occupies two floors of the RAC building, and will expand to three floors and one floor in an adjacent building, to be built, in the coming year.



The future home for IQC, currently under construction, is part of the Quantum Nano Centre. It is located at the heart of the University. The Centre comprises three buildings. One will host IQC and includes laboratories, seminar rooms, office and interaction space. Another will host the Waterloo Institute for Nanotechnology, and the final building will host a Class 100 Fabrication and Metrology facility that will be shared between the IQC and the Institute for Nanotechnology.

The QNC is a 284,000 gross square foot, five-storey facility, with a 10,000 sq ft clean room located on UW's south campus just south of the Mathematics & Computer building. It has an approved total budget of $160 million, with an average cost of $563/gross sq ft. Using the Dec 2006 Cm2r (the cost consultant retained by the University) detailed cost estimate at $125.7million for 257,000gsf ($489/gsf), the tenders were 15 per cent higher than the 2006 estimate. The various elements of the building were estimated at:

- $1600/sf for clean room & metrology $1600/sf
- $525/sf for labs
- $325/sf for offices

Below we will describe the IQC part of this centre:
The IQC building is estimated at 125,000 sq. ft. with an estimated cost of half the whole centre for a total of $80M. The contract for the building was approved by the senate in early June 2008 and was awarded the same month to the Aecon Group Inc.

See page 20 for next year's objectives related to the IQC building.

The QNC building April 29th, 2009

The Provost of the University is responsible for the project and it is coordinated by the VP Finance, Denis Huber, and the University architect, Daniel Parent. A steering committee, with the mandate to ensure the building is completed per specifications, on time and on budget, is chaired by IQC's Executive Committee Chair, and with representatives from IQC and others involved in directly overseeing the building construction.

Scott Nicoll, Special Projects and Facilities Manager and Vito Logiudice Director of Operations, Fabrication Facility oversee the development of the project for the University and interacting with the architectural firm KPMB and Aecon, on day to day issues.