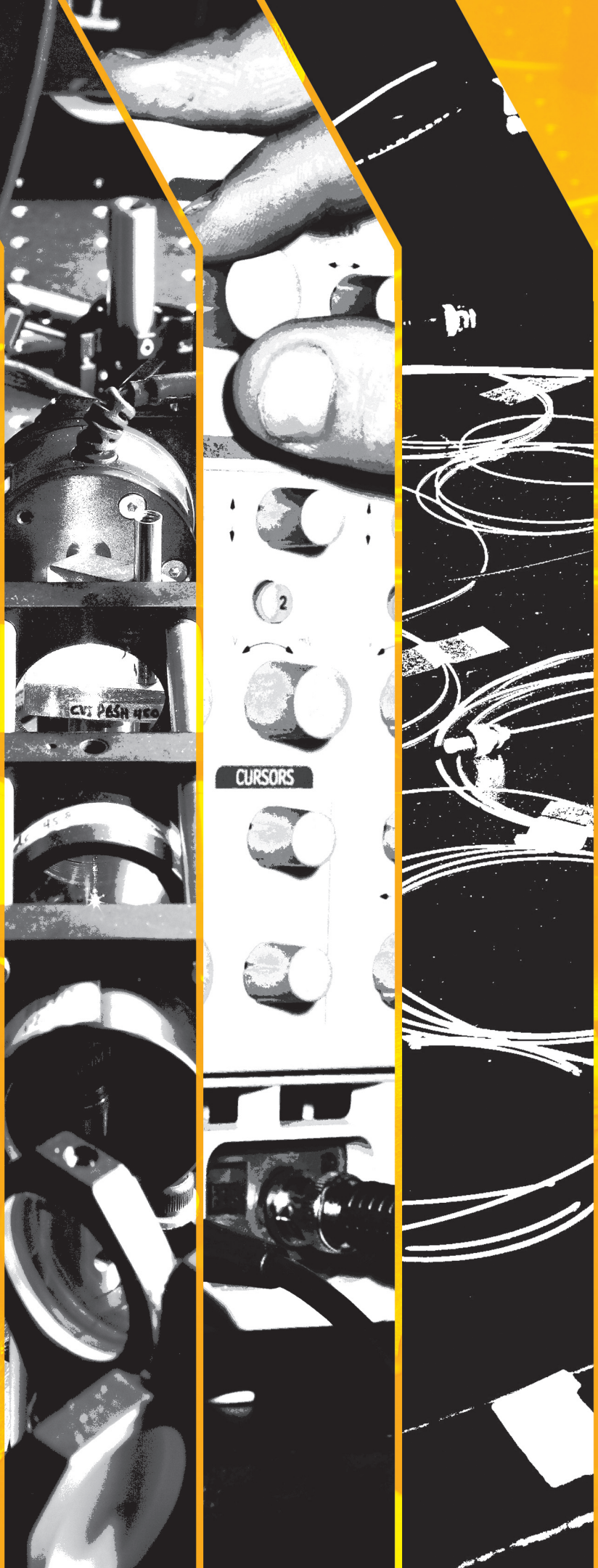
QUANTUM FRONTIERS

ANNUAL REPORT
2009-2010



Institute for
Quantum Information Science
at the University of Calgary

VISION

To be a world leader in research, teaching, and outreach in pure and applied quantum information science and technology.

MISSION STATEMENT

To conduct world-leading experimental and theoretical research in quantum information; to provide deep and diverse education and training for senior undergraduate and graduate students; and to conduct vigorous outreach and service to the public, the University, industry, and the quantum information science community.

KEY FACTS

- 7 postdoctoral associates/fellows, 34 graduate students, and 5 undergraduate students.
- 42 visiting researcher during the year including 2 long-term visiting professors and 9 long-term visiting students.
- 43 publications in refereed journal and conference proceedings with 4 published in Physical Review Letters and 2 published in Nature Photonics.
- 40 invited talks at national and international conferences/ workshops including 3 plenary talks.
- >36 poster and oral presentation done by students at national and international conferences/meetings/workshops.
- $2.5 million cash income in 2009/2010.

CONTENTS

I DIRECTOR'S REPORT

The Institute for Quantum Information Science (IQIS) at the University of Calgary is a research and a graduate and undergraduate training institute. Originally established as a University of Calgary Institute in 2005, the Institute was transferred to the Faculty of Science when the University relocated many institutes and centres to Faculties. Since its establishment, IQIS has become well known world-wide for ground-breaking inter-disciplinary research and training in the field of quantum information science and technology. The Institute's success is built in large part on recruiting the best researchers as Faculty members, postdoctoral research associates and graduate students.

Quantum information is an inter-disciplinary research area, bringing together mathematicians, computer scientists, physicists, chemists and electrical engineers. Fortunately, inter-disciplinarity is becoming increasingly recognized by universities as an important strategic direction for encouraging leading-edge research and development. However, traditional disciplinary boundaries create strong impediments for inter-disciplinary research. In the typical model of university governance, resources are funnelled from the University's top level to Faculties and thence to Departments. Department Heads rightly focus on ensuring that their Departments are supported and perform well within their respective disciplines with respect to research, training and learning. This model of governance ensures that universities are strong performers within their respective disciplines, but the price paid for this model of governance is that inter-disciplinary ventures are weakened by the often-insurmountable challenges of obtaining the most basic resources required for success.

The most important basic resources for an inter-disciplinary institute to flourish are administrative support and office space, in effect a "headquarters". Administrative support is required for operating and marketing the inter-disciplinary venture, and space is required for administration and also for enabling the inter-disciplinary delocalized team to congregate, to meet and to collaborate. Recruitment in inter-disciplinary areas is highly competitive, and the nurturing "umbrella" of the inter-disciplinary institute provides the needed supportive environment for success, interactions and reassurance to potential recruits that their inter-disciplinary research activity is indeed supported. Although Institute members are also members of discipline-based Departments, Departments are often reluctant to channel precious resources towards supporting inter-disciplinary units. Furthermore the inter-disciplinary nature of the Institute suggests sharing the burden of support, which introduces complicated political wrangling into the process of gaining support. In my experience, only direct funding, allocated space and moral support by the supporting unit (e.g. Faculty) are effective; indirect support is insecure and takes a lot of energy and time to obtain and to maintain.

Another challenge impeding inter-disciplinary efforts is that faculty hiring plans are constructed by Departments and can overlook the importance and timeliness of rapid hiring in an emerging inter-disciplinary area. Therefore, it is important that inter-disciplinary institutes be regarded as key stakeholders in decision-making regarding future faculty hires. The final major challenge is that inter-disciplinarity poses communication challenges for supporting colloquia, seminars and visitors that are so important to bind together the members of the inter-disciplinary unit.

Kudos go to *i*CORE and to the University of Calgary leadership for having had the vision and courage to support inter-disciplinary activities. IQIS is one of the fruits of this University of Calgary tree of inter-disciplinarity. These successes of inter-disciplinarity were achieved with active support by two sequential *i*CORE Presidents Brian Unger (now on the IQIS Board) and Randy Goebel and by University of Calgary President Harvey Weingarten, the University of Calgary Vice-President (Research & International) Dennis Salahub and two sequential Deans of Science: Michael Boorman and Sandy Murphree. These individuals provided moral support, financial assistance and an appropriate

blend of activism and patience; without this support IQIS and its achievements would not have been possible.

In return for this support, the Institute for Quantum Information is expected, even required, to excel. This excellence is not just about performance of research groups within the Institute but also success as an inter-disciplinary institute in its own right. The Institute's raison d'être is to create, nurture and sustain an inter-disciplinary effort in quantum information so that research groups are excellent in their own right and so that the whole is greater than the sum of the parts: research groups interact, collaborate and learn from each other to engage in research and achieve results that would not be achieved without the Institute establishing this inter-disciplinary environment.

For a small investment, IQIS is delivering on these aims. Faculty members are recognized as outstanding. The IQIS Director is an *i*CORE Chair and recognized for his achievements through fellowships of the Canadian Institute for Advanced Research and several professional societies. Other faculty members have externally-funded research Chairs and are Scholars of the Canadian Institute for Advanced Research. Lvovsky is a recipient of the prestigious 2010 International Quantum Communication Award. IQIS faculty members and their research groups are conducting excellent research programs and, furthermore, are working together and within inter-disciplinary quantum information projects beyond the University of Calgary, as attested to by joint journal publications.

The Institute itself continues to grow in size. IQIS membership is strong, increasing from 63 in 2009 to 68 in 2010, making it one of the largest and most productive quantum information centres in the world. Graduating students and postdoctoral fellows moved from IQIS to further academic studies, to research and professorial positions and to industry. Former IQIS students have continued post-IQIS studies at other top institutes of learning including the University of Toronto and the Max Planck Institute for the Science of Light. Examples of industrial positions assumed by IQIS alumni are at the China Academy of Space Technology and with General Dynamics Canada in Calgary. Postdoctoral researchers moved to new postdoctoral positions at Polytechnique Montréal, Queen Mary College of the University of London and the University of Bristol. One postdoctoral researcher who completed her term in IQIS, Peng Xue, went directly to a full Professor position at Southeast University in Nanjing. IQIS alumni success are the best evidence of the quality and value provided by the Institute, and IQIS alumni are making impressive advances at their new sites.

IQIS is also an exemplar of outreach and service. Animated films for quantum information educational purposes are now available freely on YouTube. The IQIS Director is Chair of the Canadian Association of Physicists Division of Atomic and Molecular Physics and Photon Interactions and also Chair of the Optical Society of America Quantum Optical Science and Technology Technical Group as well as being Chair or committee member of various conferences, professional society committees, Editorial Boards and research grant agency panels. Wolfgang Tittel was co-Chair of last year's *i*CORE Summit. Other IQIS faculty members are serving on various international committees, but most are at a junior level so their real service work will be strong in a few years.

The international standing of IQIS is particularly evident through membership in national and international research networks. IQIS is a partner of the three-year collaborative student training program "Quantum Information Processing" supported by the EU-Canada Programme for Cooperation in Higher Education, Training and Youth, which is jointly funded by the European Commission's Directorate General for Education and Culture and Human Resources and Skills Development Canada. This research network gives graduate students in Canada and the EU exposure especially to study opportunities in quantum information processing with partners. IQIS members are also partners in the France-Canada Strategic Project called "Frequency", supported by NSERC and Agence Nationale de la Recherche (France). Frequency was launched in February 2010 and focuses on quantum cryptography.

Within Canada, IQIS members are in the Canadian Institute for Advanced Research program on quantum information processing and leader of two mathematically-oriented quantum information networks: the quantum information processing program within the Network of Centres of Excellence for Mathematics of Information Technology and Complex Systems and the

"Collaborative Research Group for the Mathematics of Quantum Information" within the Pacific Institute for Mathematical Sciences. IQIS continues a productive partnership with General Dynamics Canada and is exploring other industrial partnerships, especially with respect to spin-off benefits of quantum information technology research.

On a scientific level, excellent results have been achieved and are detailed in this Annual Report. Also of note, quantum information research is becoming entangled with other research activities in the province. A collaboration between IQIS Director Sanders's group and *i*CORE Chair Wolkow's group at the National Institute for Nanotechnology (NINT) in Edmonton has yielded promising results on how dangling bonds on the surface of silicon can enable quantum information processing. The collaboration between NINT and IQIS is destined to grow with the appointment of a new IQIS Faculty member who will be seconded 50% of the time to NINT. In another direction, Sanders and Institute for Biocomplexity and Informatics Director Dennis Salahub have a productive collaboration on quantum transport of electrons in protein complexes for reduction-oxidation reactions. This research effort shows that a protein complex builds a stable bridge comprising a single water molecule, which enables the electron to cross a bridge rather than quantum tunnel through the gap.

IQIS is delivering significant research outcomes in diverse areas and therefore is living up to its mandate within the University of Calgary's Faculty of Science. IQIS will continue to strive to conduct outstanding research and development, recruit top people, build collaborations with other quantum information centres, other research groups within Alberta and industrial partners. For IQIS to reach its full potential, support for IQIS needs to be secure and ongoing, critical mass must be built in the Departments of Mathematics & Statistics and Computer Science, and better linkage to the Faculty of Engineering, perhaps aided by future Faculty hires, is important.

Barry Sanders, Director, IQIS

II QUANTUM INFORMATION RESEARCH GROUPS AT THE INSTITUTE

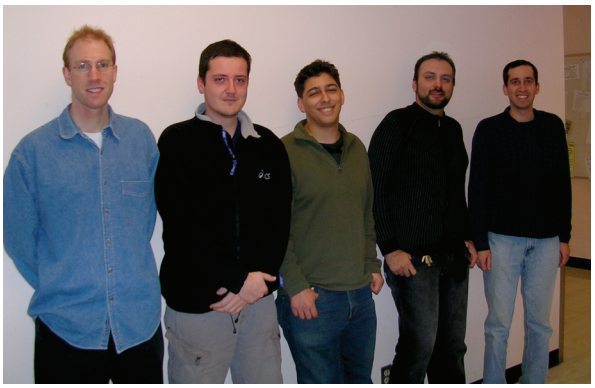
Practical Approaches to Quantum Computation

DR. DAVID FEDER

Quantum computers have the potential to solve numerous problems more efficiently than the best-known classical computers, but so far only very small, proof-of-principle quantum computers have been built. The research of our group is focused mainly on understanding how the intrinsic properties of physical systems, such as ultracold atomic gases or spin lattices, can be employed to construct larger devices able to perform quantum computation. In the process, we are exploring alternative models for the implementation of quantum logic, such as one-way quantum computation, quantum walks, and topological quantum computation.

Quantum Information Theory

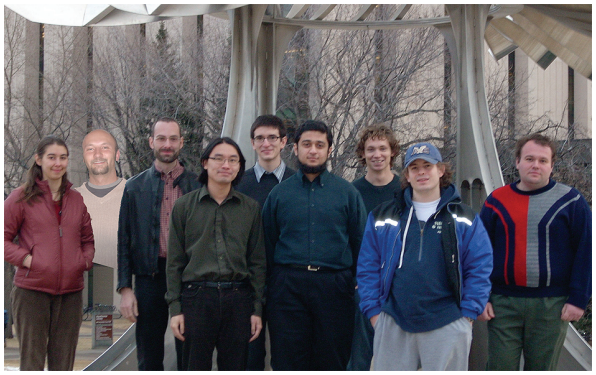
DR. GILAD GOUR



Quantum resources, like entanglement, are the key ingredients of quantum information processing tasks. They are needed in many cases where quantum networks contain certain kinds of limitations or imperfections. For example, situations in which parties in the network are not familiar with the exact orientation of each other (i.e. they are lacking a shared reference frame) induce limitations called super-selection rules. With such restrictions new quantum resources are needed. Our group objectives are to study the fascinating resource theories that emanate from such constraints. The study of quantum information in the presence of super-selection rules, for example, not only leads to new, interesting physics and the discovery of new resource, but also has applications in related fields, such as quantum cryptography, quantum optics, and quantum communication.

Quantum Computing

DR. PETER HØYER



The Quantum Computing Research Group within the Department of Computer Science conducts research in computational aspects of quantum mechanical systems. Quantum computers are in particular interesting because they offer a possibility to achieve computations that cannot be easily achieved on traditional computers. We utilize the potential powers of quantum systems to develop quantum algorithms, quantum communication protocols, and quantum computer simulations of quantum mechanical systems. We conduct work on characterizing these powers and the limitations by studying quantum complexity theory, non-locality, entanglement, and quantum information theory. We organized and hosted the Third and Sixth Canadian Summer School on Quantum Information Processing.

Quantum Information Technology with Light and Experimental Quantum Optics

DR. ALEX LVOVSKY

Photons are excellent carriers of quantum information. One can build an entire quantum information processor by means of single-photon sources, detectors, and simple linear optical elements such as mirrors and beam splitters. Our group concentrates on implementing light for the purposes of quantum information technology – that is, learning to synthesize, control, characterize, and store arbitrary quantum states of the electromagnetic field.

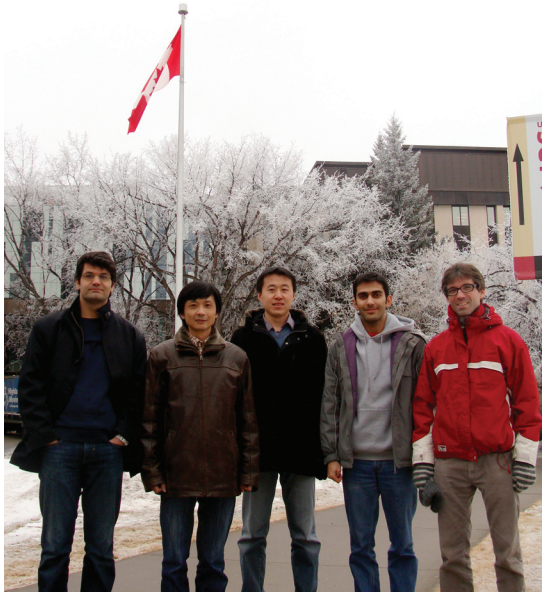
Quantum Information Science

DR. BARRY SANDERS

Our aim is to develop quantum information technologies that have transformative applications and will be feasible within a decade. The research program is divided into five strands: (i) long-distance secure communication, (ii) simulations of complex systems, (iii) implementations of quantum information tasks, (iv) empirical characterization of quantum states and processes, and (v) determining and quantifying all resources for quantum information processing.

Theoretical Quantum Optics

DR. CHRISTOPH SIMON



The interaction of light and matter at the quantum level played a major role in the development of quantum physics. Its detailed study in the field of quantum optics has led to the development of important applications such as the laser, and to the first experimental ademonstrations of the most striking features of quantum physics, such as entanglement and quantum non-locality. However, quantum optics is not ready to rest on its laurels. There are two key future challenges. On the one hand, we strive to develop genuine applications of these fundamental quantum features. Our group is particularly interested in the development of quantum repeaters, which will be essential for future long-distance quantum communication. This motivates us to study potential implementations of quantum memories and of quantum gates between individual photons in various systems. On the other hand, quantum optical systems are ideally positioned to explore the quantum-classical transition, allowing us to deepen our understanding of how the classical macroscopic world arises out of microscopic quantum behaviour. This motivates us to study the quantum amplification of photons to macroscopic levels, as well as quantum opto-mechanical systems.

Quantum Cryptography and Communication

DR. WOLFGANG TITTEL

Photons and atoms are key constituents for long distance quantum communication and quantum networks. Our group's effort focuses on building photon-based quantum cryptography systems through optical fibres, and targets the development of a quantum repeater to extend quantum cryptography past its current distance limit. This includes developing novel techniques for rendering photonic quantum communication primitives such as quantum teleportation practical, plus hitherto unrealized means for efficient and reversible transfer of quantum information between photons and atoms for temporal storage.

III MANAGEMENT

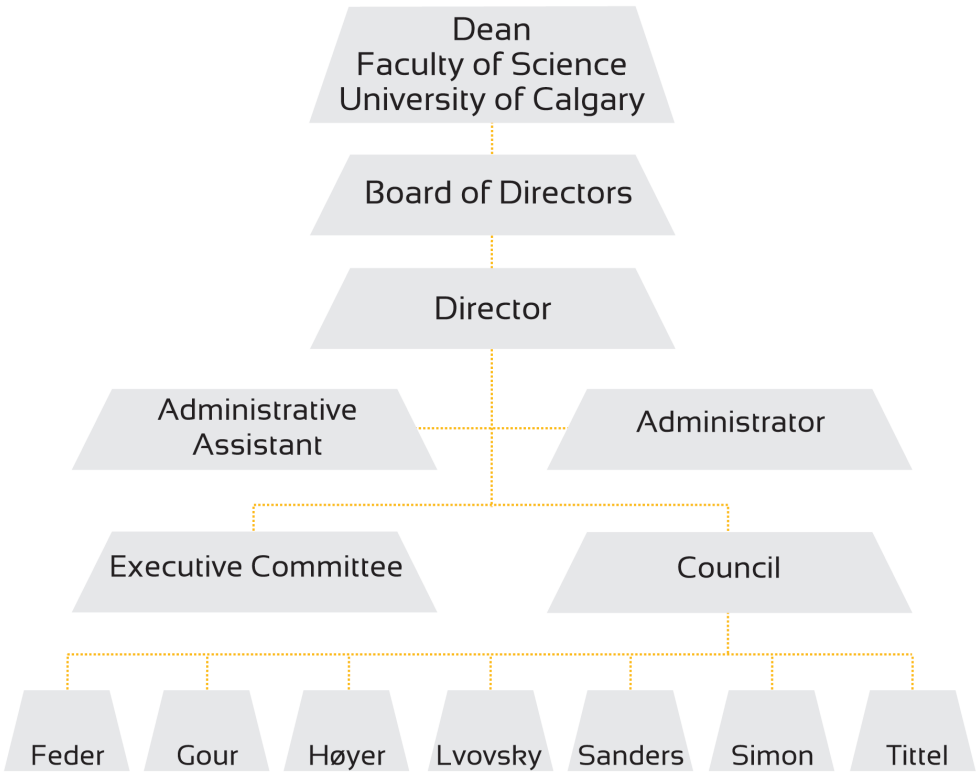
A. Structure

The organizational structure of the Institute is depicted in the organizational chart below. The Institute is managed on a day-to-day level by the Institute Director and the Institute Administrator. The Director and his research group are additionally supported by an administrative assistant. The Director reports to the Board of Directors and is ex officio a member of this Board. The Board reports to the Dean of Faculty of Science who chairs the Board.

The Director and the Administrator of the Institute work on day-to-day matters of the Institute. The Institute Executive comprises the Director, Deputy Director, Administrator, and two faculty members other than the Director and Deputy Director. The Executive meets monthly to discuss and make decisions on executive matters. The Executive receives advice and guidance from the IQIS Council, which comprises all full and affiliate faculty members of the Institute.

All of the Institute's research, teaching, service, and outreach activities are conducted by faculty members and their research groups.

Organizational Chart – Institute for Quantum Information Science



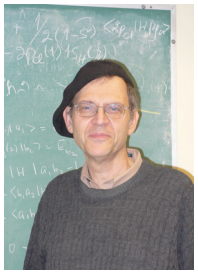
B. Board of Directors

CHAIR

Dr. J. Sandy Murphree
Dean, Faculty of Science, University of Calgary

Dr. J. S. (Sandy) Murphree is an experienced space physicist who came to the University of Calgary in 1975 as a Postdoctoral Fellow. He served as a Research Associate, and Adjunct Associate Professor before being appointed as an Associate Professor in 1988. In 1991 Dr. Murphree was promoted to Professor, and in 1995 he became Head of the Department of Physics and Astronomy until June 2000. He was appointed Associate Dean (Research and Academic Affairs) in July 2003, with the title changing to Vice-Dean a year later. He became Acting Dean in July 2005, and in March 2006 he became Dean of Science. His term as Dean will finish on June 30, 2010.

MEMBERS



Dr. Paul Brumer
Professor, Department of Chemistry, Faculty of Arts and Science, University of Toronto

Dr. Brumer joined University of Toronto in 1975 after completing his BSc at Brooklyn College and his PhD at Harvard University and was appointed a University Professor in 1995. Dr. Brumer has been at the forefront of two major areas in chemical physics: using nonlinear mechanics to understand molecular dynamics, and controlling chemicalreactions with lasers.

Dr. Brumer's work has been recognized in numerous ways. He has been an A.P. Sloan Foundation Fellow and is a Fellow of the Royal Society of Canada, the Chemical Institute of Canada and the American Physical Society. He has received two Canada Council Killam Research Fellowships and is one of the youngest recipients of the CIC Palladium Medal, the highest award of the Chemical Institute of Canada. He was the recipient of the prestigious 2000 Killam Memorial Prize in Physical Sciences and is currently both a Distinguished University Professor and the Roel Buck Chair in Chemical Physics at the University of Toronto.

Dr. Jim Haslett
Professor, Department of Electrical and Computer Engineering, University of Calgary

Dr. Haslett holds the position of "University Professor" and is also a Professor in the Department of Electrical and Computer Engineering at the University of Calgary. He has been an academic staff member at the University of Calgary for the past 39 years, and was the Head of the Department from 1986 to 1997.

Dr. Haslett is currently the Principal Investigator of the *i*CORE-funded Advanced Technology Information Processing Systems (ATIPS) Lab at the University of Calgary, and is also co-director of the Advanced Micro/nanosystems Integration Facility (AMIF) at the University. He held the TRLabs/*i*CORE/NSERC Senior Industrial Research Chair in Wireless Communications from 2002 to 2007, building a team of researchers specializing in radio frequency integrated circuit (RFIC) design for wireless communications applications. He has published over 200 papers in peer-reviewed journals and conference proceedings, and holds 12 patents, many of which have been licensed to industry. He has graduated over 40 MSc and PhD students during his career.

Dr. Haslett is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), a Fellow of the Engineering Institute of Canada, and a Fellow of the Canadian Academy of Engineering. He and his students have won numerous national and international awards for their research work. He is currently a member of the Editorial Review Committees of five IEEE Transactions, is a member of several technical and executive committees of international IEEE Conferences, and is also a member of the provincial *i*CORE internal review committee which establishes research chair programs in Alberta.

Professor Sir Peter Knight
Deputy Rector (Research), Imperial College London

Professor Sir Peter Knight is Deputy Rector (Research) at Imperial College, London U.K., and is past Head of Imperial's Department of Physics. He is a past President of the Optical Society of America and a past Chair of the European Physical Society's Quantum Electronics and Optics Division, and has been Chief Scientific Advisor to the UK National Physical Laboratory. He is chair of the UK Government Defence Scientific Advisory Committee.

Professor Sir Peter Knight is renowned for research in quantum optics, strong field physics, and quantum information and is widely recognized for both his research and communication abilities and achievements, including having been a Parsons Memorial Lecturer in 1991, Wood Memorial Lecturer in 1996, and winner of the Thomas Young Medal and Prize in 1996. He is the 2008 winner of the Optical Society of America's Ives Medal and the 2009 Glazebrook Medal and Prize of the Institute of Physics.

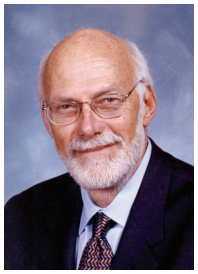
Dr. Greg Luoma
President, LuomaTech Inc.

Dr. Luoma has over 25 years of experience conducting, managing, and directing large and diverse technology development programs in defence and public security. He also has internationally recognized technical expertise in defence against Weapons of Mass Destruction, in advanced materials and analytical chemistry. He has published extensively in the open literature, has represented the Canadian government and GD Canada on numerous international technical panels, and has been an invited speaker at many international technical conferences and military symposia. Dr. Luoma holds BSc, MSc and PhD degrees in Chemistry from the University of British Columbia.

In January 2009, Dr. Luoma initiated his own company, LuomaTech Inc., to provide technical and strategic business consulting services to Defence and security organizations.

From 2004 to 2008, Dr. Luoma served as Chief Technology Officer for GD Canada, successfully re-inventing the company's technology strategy as well as maintaining oversight for all R&D. From 1998 to 2004, Dr. Luoma held positions at GD Canada as Director of R&D and Chief Scientist, successfully aligning internal R&D with business goals.

From 1992 to 1998, Dr. Luoma served as Section Head, Chemical and Biological Defence, at Defence Research and Development Canada (DRDC) Suffield. Prior to his term at DRDC Suffield, he was a Group Leader at the Defence Research Establishment Pacific, leading a group providing analytical chemistry support to the Canadian Navy in Victoria while conducting research into the use of advanced materials in military platforms.



Dr. Brian Unger
Executive Director, Grid Research Centre
Professor, Department of Computer Science, University of Calgary

Dr. Unger is Professor Emeritus, Faculty Professor, and the Executive Director of the Grid Research Centre within the Faculty of Science at the University of Calgary. He is the Special Advisor for iREACH ("informatics for rural empowerment and community health"), a research project supported by the International Development Research Centre of Canada (IDRC) and by the Cambodian Ministry of Commerce (ireach.org.kh). Dr. Unger is past President and CEO of Cybera Inc. (www.cybera.ca). He was the founding President of the Netera Alliance that is now Cybera Inc. and the founding President of *i*CORE from 1999 through 2004.

Dr. Unger was the founding board chair of C3.ca Inc., a national consortium aimed at building Canada's infrastructure in high performance computation. C3.ca was one of the originators of the current Compute Canada initiative. He was a Co-Principal Investigator of WestGrid (www.westgrid.ca) from 2002 to 2008, which raised $48 million to provide research infrastructure for Western Canadian universities. He was the founding president and CEO of a for-profit startup company, Jade Simulations, that developed and marketed parallel simulation software products from 1988 through 1993.

Dr. Unger was named a Canada Pioneer of Computing at the IBM CASCON conference in Toronto in October 2005. He received the IWAY Public Leadership award for outstanding contributions to Canada's information society in 2004, and the 1993 ASTech award for "Innovation in Alberta Technology" for research in parallel simulation and distributed computation.

DIRECTOR

Dr. Barry C. Sanders
*i*CORE Chair of Quantum Information Science

Dr. Barry Sanders is *i*CORE Chair of Quantum Information Science and Director of the Institute for Quantum Information Science at the University of Calgary. He received his Bachelor of Science degree from the University of Calgary in 1984 and then completed a Diploma of Imperial College under the supervision of Professor T. W. B. Kibble. Subsequently he completed a PhD at Imperial College under the supervision of Professor Sir Peter Knight. Following completion of the PhD in 1987, he was a postdoctoral research fellow under the supervision of Professor Gerard Milburn, first at the Australian National University and then at the University of Queensland, and also under the supervision of Professor Crispin Gardiner who was then at the University of Waikato. Dr. Sanders joined the Physics Department of Macquarie University in 1991 and was there for 12 years, including 6.5 years as Department Head, before moving to Calgary in 2003.

Dr. Sanders is especially well known for seminal contributions to theories of quantum-limited measurement, highly nonclassical light, practical quantum cryptography, and optical implementations of quantum information tasks. His current research interests include quantum resources and algorithms and also optical and atomic implementations of quantum information tasks and protocols. Recently Dr. Sanders has developed research activities in quantum processes in biological systems and also on machine learning approaches to quantum control.

Dr. Sanders is a Fellow of the Institute of Physics (U.K.), the Optical Society of America, the Australian Institute of Physics, the American Physical Society, and the Canadian Institute for Advanced Research. He is a past President of the Australian Optical Society, former Secretary-Treasurer of the American Physical Society Topical Group on Quantum Information, Chair of the Canadian Association of Physicists Division of Atomic and Molecular Physics and Photonic Interactions, a member of the American Institute of Physics Education Advisory Committee, and an editorial board member for Physical Review A, New Journal of Physics, Optics Communications, and Applied Mathematics and Information Sciences. He also serves the Optical Society of America as Leader of the Quantum Optical Science and Technology Technical Group.

IV PERFORMANCE AND ANALYSIS

A. Research and Development

1. Refereed publications

M. Adcock, P. Høyer and B. C. Sanders, "Limitations on continuous variable quantum algorithms with Fourier transforms", *New Journal of Physics* **11**: 103035 (24 pp.), 21 October 2009.

J. Appel, A. MacRae and A. I. Lvovsky, "Versatile digital GHz phase lock for external cavity diode lasers", *Measurement Science and Technology* **20**(5): 055302 (5 pp.), 17 April 2009.

T. R. Beals, K. P. Hynes and B. C. Sanders, "Distributed authentication for randomly compromised networks", *New Journal of Physics* **11**(8): 085005 (13 pp.), 21 August 2009.

E. Bimbard, N. Jain, A. MacRae and A. I. Lvovsky, "Quantum-optical state engineering up to the two-photon level", *Nature Photonics* **4**(4): 243 – 247, 14 February 2010.

F. Buscemi, G. Gour and J. S. Kim, "Polygamy of distributed entanglement", *Physical Review A* **80**(1): 012324 (8 pp.), 20 July 2009. (Selected for the August 2009 issue of Virtual Journal of Quantum Information).

G. Campbell, A. Ordog and A. I. Lvovsky, "Multimode electromagnetically-induced transparency on a single atomic line", *New Journal of Physics* **11**(10): 103021 (9 pp.), 7 October 2009.

C. Dohotaru and P. Høyer, "Exact quantum lower bound for Grover's problem", *Quantum Information and Computation* **9**(5-6): 533 – 540, 1 May 2009.

A. G. D'Souza, J. Briet and D. L. Feder, "Testing equivalence of pure quantum states and graph states under SLOCC", *International Journal of Quantum Information* **8**(1–2): 395 – 410, 1 February 2010.

S. Ghose, N. Sinclair, S. Debnath, P. Rungta and R. Stock, "Tripartite entanglement versus tripartite nonlocality in three-qubit greenberger-horne-zeilinger-class states", *Physical Review Letters* **102**(25): 250404 (4 pp.), 26 June 2009.

G. Gour, B. C. Sanders and P. S. Turner, "Time reversal frameness and superselection", *Journal of Mathematical Physics* **50**(10): 102105 (11 pp.), 19 October 2009. (Selected for the November 2009 issue of Virtual Journal of Quantum Information).

A. Hentschel and B. C. Sanders, "Machine learning for precise quantum measurement", *Physical Review Letters* **104**(6): 063603 (4 pp.), 11 February 2010.

S. R. Huisman, N. Jain, S. A. Babichev, F. Vewinger, A.-N. Zhang, S.-H. Youn and A. I. Lvovsky, "Instant single-photon Fock state tomography", *Optics Letters* **34**(18): 2739 – 2741, 15 September 2009.

J. Joo, T. Rudolph and B. C. Sanders, "A heralded two-qutrit entangled state", *Journal of Physics B: Atomic, Molecular and Optical Physics* **42**(11): 114007 (8 pp.), 15 May 2009.

J. Joo and D. L. Feder, "Error-correcting one-way quantum computation with global entangling gates", *Physical Review A* **80**(3): 032312 (11 pp.), 11 September 2009. (Selected for the September 2009 issue of Virtual Journals of Quantum Information, Applications of Superconductivity, and Nanoscale Science & Technology).

J. S. Kim and B. C. Sanders, "On the geometric distance between quantum states with positive partial transposition and private states", *Letters in Mathematical Physics* **92**(1): 67 – 79, 25 February 2010.

J. S. Kim, "Polygamy of entanglement in multipartite quantum systems", *Physical Review A* **80**(2): 022302 (3 pp.), 4 August 2009. (Selected for the August 2009 issue of Virtual Journal of Quantum Information).

K. Kuntz, B. Braverman, S.-H. Youn, M. Lobino, E. M. Pessina and A. I. Lvovsky, "Spatial and temporal characterization of a Bessel beam produced using a conical mirror", *Physical Review A* **79**(4): 043802 (5 pp.), 2 April 2009.

M. Lobino, C. Kupchak, E. Figueroa and A. I. Lvovsky, "Memory for light as a quantum process", *Physical Review Letters* **102**(20): 203601 (4 pp.), 19 May 2009.

I. Lucio Martinez, P. Chan, X. F. Mo, S. Hosier and W. Tittel, "Proof-of-concept of real-world quantum key distribution with quantum frames", *New Journal of Physics* **11**(9): 095001 (26 pp.), 2 September 2009.

A. I. Lvovsky, "Protecting quantum superpositions from the outside world", *Physics* **2**: 83 (3 pp.), 5 October 2009.

A. I. Lvovsky, B. C. Sanders and W. Tittel, "Quantum optical memory", *Nature Photonics* **3**(12): 706 – 714, 30 November 2009.

K.-P. Marzlin, Z.-B. Wang, S. A. Moiseev and B. C. Sanders, "Uniform cross phase modulation for nonclassical radiation pulses", *Journal of the Optical Society of America B* **27**(6): A36 – A45, 12 March 2010.

S. A. Moiseev, A. A. Kamli and B. C. Sanders, "Low-loss nonlinear polaritonics", *Physical Review A* **81**(3): 033839 (5 pp.), 23 March 2010.

T. A. Osborn and K.-P. Marzlin, "Moyal phase-space analysis of nonlinear optical Kerr media", *Journal of Physics A: Mathematical and Theoretical* **42**(41): 415302 (19 pp.), 16 October 2009.

A. Roy, "Minimal euclidean representations of graphs", *Discrete Math* **310**(4): 727 – 733, 25 September 2009.

A. Roy and A. J. Scott, "Unitary designs and codes", *Designs, Codes and Cryptography* **53**(1): 13 – 31, 23 April 2009.

B. C. Sanders, "Algorithm for quantum simulation", *Applied Mathematics and Information Sciences* **3**(2): 117 – 122, 1 May 2009.

Y. R. Sanders and G. Gour, "Necessary conditions for entanglement catalysts", *Physical Review A* **79**(5): 054302 (4 pp.), 6 May 2009.

A. Scherer, R. B. Howard, B. C. Sanders and W. Tittel, "Quantum states prepared by realistic entanglement swapping", *Physical Review A* **80**(6): 062310 (20 pp.), 4 December 2009. (Selected for the December 2009 issue of Virtual Journal of Quantum Information).

J. A. Slater, J.-S. Corbeil, S. Virally, F. Bussières, A. Kudlinski, G. Bouwmans, S. Lacroix, N. Godbout and W. Tittel, "A microstructured fiber source of photon pairs at widely separated wavelengths", *Optics Letters* **35**(4): 499 – 501, 15 February 2010.

J. B. Stang, A. T. Rezakhani and B. C. Sanders, "Correlation effects in a discrete quantum random walk", *Journal of Physics A: Mathematical and Theoretical* **42**(17): 175304 (11 pp.), 7 April 2009.

W. Tittel, M. Afzelius, T. Chanelière, R. L. Cone, S. Kröll, S. A. Moiseev and M. Sellars, "Photon-echo quantum memory in solid state systems", *Laser & Photonics Reviews* **4**(2): 244 – 267, 23 March 2009.

M. S. Underwood and K.-P. Marzlin, "Fermi-Frenet coordinates for space-like curves", *International Journal of Modern Physics A* **25**(6): 1147 – 1154, 10 March 2010.

N. Wiebe, D. W. Berry, P. Høyer and B. C. Sanders, "Higher order decompositions of ordered operator exponentials", *Journal of Physics A: Mathematical and Theoretical* **43**(6): 065203 (20 pp.), 22 January 2010.

P. Xue, B. C. Sanders and D. Leibfried, "Quantum walk on a line for a trapped ion", *Physical Review Letters* **103**(18): 183602 (4 pp.), 28 October 2009. (Selected for the November 2009 issue of Virtual Journal of Quantum Information).

2. Professional magazine

None.

3. Book chapter

A. R. Weily, T. S. Bird, K. P. Esselle and B. C. Sanders, "EBG materials and antennas", section in book: *Advanced Millimeter-wave Technologies*, D. Liu, B. Gaucher, U. Pfeiffer and J. Grzyb, eds., **Chapter 10**, Published by Wiley, pp. 413 to 444, 2009.

4. Editorial

G. Messin, B. C. Sanders, D. Petrosyan and J. Rarity, "Few-photon optics", *Journal of Physics B: Atomic, Molecular and Optical Physics* **42**(11): 110201 (1 p.), 14 June 2009.

5. Editorship

G. Messin, B. C. Sanders, D. Petrosyan and J. Rarity, "Special Issue on few-photon optics", *Journal of Physics B: Atomic, Molecular and Optical Physics* **42**(11), Published by IOP Publishing, 14 June 2009.

6. Conference proceedings

F. Buscemi, G. Gour and J. S. Kim, "Polygamy of distributed entanglement", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 8 – 9, 26 August 2009.

J. S. Kim, A. Das and B. C. Sanders, "Entanglement monogamy of multipartite higher-dimensional quantum systems using convex-roof extended negativity", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 23 – 24, 26 August 2009.

J. S. Kim and B. C. Sanders, "On the geometric distance between quantum states with positive partial transposition and private states", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 60 – 61, 26 August 2009.

J. S. Kim, "Polygamy of entanglement in multipartite quantum systems", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 10 – 11, 26 August 2009.

X. F. Mo, I. Lucio Martinez, P. Chan, S. Hosier and W. Tittel, "Quantum key distribution with quantum frames", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 66 – 67, 26 August 2009.

Y. J. Wang, B. C. Sanders, B.-M. Bai and X. M. Wang, "Feedback iterative decoding of sparse quantum codes", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug

2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 79 – 80, 26 August 2009.

P. Xue, "Efficient, scalable generation of cluster states in charge qubits", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 91 – 92, 26 August 2009.

P. Xue, B. C. Sanders and D. Leibfried, "Quantum walk on a line for a trapped ion", Proceedings of The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009, Published by Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China: 50 – 51, 26 August 2009.

7. Patents

S. Moiseev, A. A. Kamli and B. C. Sanders, "Fast all-optical switch for weak fields", filed provisional patent on 14 May 2009.

8. Presentations (presenter is underlined)

1 Apr 2009, B. C. Sanders, "Electron superhighway through a protein complex", Universität Innsbruck, Institut für Theoretische Physik.

6 Apr 2009, A. I. Lvovsky, "Memory for light as a component of quantum communication systems", Universität Mainz, Institut für Physik.

7 Apr 2009, D. L. Feder, "Can the ground states of low-dimensional many-body systems be useful for quantum computation?", Université Paris-Sud, Laboratoire de Physique Théorique et Modèles Statistiques, Département de Physique.

15 Apr 2009, D. L. Feder, "Cooling ultracold bosons in optical lattices by quantum walks", University of Hamburg, Institute for Laser Physics.

17 Apr 2009, D. L. Feder, "Cooling ultracold bosons in optical lattices by quantum walks", Aarhus University, Department of Physics and Astronomy.

22 Apr 2009, D. L. Feder, "Cooling ultracold bosons in optical lattices by quantum walks", University of Hannover, Institute for Quantum Optics, Faculty of Mathematics and Physics.

24 Apr 2009, D. L. Feder, "Cooling ultracold bosons in optical lattices by quantum walks", Gutenberg University, Institute for Quantum, Atom, and Neutron Physics.

24 Apr 2009, A. Hentschel, "Achievable bitrates for quantum key distribution", University of Calgary, Department of Computer Science.

29 Apr 2009, A. Hentschel and B. C. Sanders, "Machine learning for adaptive quantum control and measurement", University of Calgary, Institute for Quantum Information Science.

5 May 2009, J. Joo and D. L. Feder, "Error-correcting one-way quantum computation with global entangling gates" (poster), ICTP Conference on Research Frontiers in Ultra-Cold Atoms, Trieste, Italy, 4 May 2009 – 8 May 2009.

5 May 2009, D. L. Feder, "Fermions in lattices as a universal resources for quantum information processing" (poster), ICTP Conference on Research Frontiers in Ultra-Cold Atoms, Trieste, Italy, 4 May 2009 – 8 May 2009.

11 May 2009, C. La Mela, A. Delfan, E. Saglamyurek and W. Tittel, "Quantum memories: storage and state transformation" (contributed), Rare-earth Doped Solids for Quantum Information, Lund, Sweden, 11 May 2009 – 12 May 2009.

21 May 2009, G. Berlin, G. Brassard, F. Bussières, N. Godbout, J. A. Slater and W. Tittel, "Loss-tolerant quantum coin flipping", Biannual INTRIQ Workshop, Orford, Canada, 21 May 2009 – 22 May 2009.

23 May 2009, M. Lobino, "Coherent state quantum process tomography" (invited), Bulletin of the American Physical Society **54**(7): W6.00002, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP 2009), Charlottesville, United States of America, 19 May 2009 – 23 May 2009 (http://meetings.aps.org/link/BAPS.2009.DAMOP.W6.2).

24 May 2009, A. A. Kamli, S. A. Moiseev and B. C. Sanders, "Quantum memory for surface polaritons in metamaterials", 16th Central European Workshop on Quantum Optics (CEWQO 2009), Turku, Finland, 23 May 2009 – 27 May 2009.

25 May 2009, A. Scherer and B. C. Sanders, "Quantum states after N concatenated entanglement swappings under real-world conditions" (invited), 2009 PIMS Industrial Problem Solving Workshop and Graduate Industrial Mathematics Modelling Camp, Calgary, Canada, 19 May 2009 – 29 May 2009.

27 May 2009, A. I. Lvovsky, "Constructing light: photon by photon", York University, Department of Physics and Astronomy.

28 May 2009, A. Hentschel and B. C. Sanders, "Machine learning for adaptive quantum control and measurement" (contributed), *i*CORE Quantum Information Science @ University of Calgary Mini-Conference, Calgary, Canada, 28 May 2009.

28 May 2009, A. Scherer, B. C. Sanders and W. Tittel, "Quantum states prepared by real-world entanglement swapping" (contributed), *i*CORE Quantum Information Science @ University of Calgary Mini-Conference, Calgary, Canada, 28 May 2009.

28 May 2009, Z. Shaterzadeh Yazdi, P. Xue, B. C. Sanders, L. Livadaru, J. L. Pitters, G. A. DiLabio and R. A. Wolkow, "Quantum computing with dangling bond pairs on a silicon

surface " (contributed), *i*CORE Quantum Information Science @ University of Calgary Mini-Conference, Calgary, Canada, 28 May 2009.

3 Jun 2009, F. Buscemi, G. Gour and J. S. Kim, "Polygamy of distributed entanglement" (contributed), Mathematics of Information Technology and Complex Systems Annual Conference 2009 (MITACS 2009), Fredericton, Canada, 31 May 2009 – 5 Jun 2009.

5 Jun 2009, P. Xue, B. C. Sanders, A. Blais, K. Lalumière and D. Leibfried, "Implementing quantum walks" (invited), Theory Canada 5, Fredericton, Canada, 3 Jun 2009 – 6 Jun 2009.

7 Jun 2009, A. Roy, "Minimal Euclidean representations of graphs" (invited), Canadian Mathematical Society Meeting (CMS Summer 2009), St. John's, Canada, 6 Jun 2009 – 8 Jun 2009.

9 Jun 2009, I. Lucio Martinez, P. Chan, X. F. Mo, S. Hosier and W. Tittel, "Quantum key distribution with quantum frames " (contributed), TU-A4-3, *Physics in Canada* **65**(2):p. 85, Canadian Association of Physicists Congress (CAP Congress 2009), Moncton, Canada, 7 Jun 2009 – 10 Jun 2009.

9 Jun 2009, N. Sinclair, E. Saglamyurek, C. La Mela and W. Tittel, "Tm:$LiNbO_3$ waveguides: a novel material candidate for quantum memories" (contributed), TU-P5-3, *Physics in Canada* **65**(2):p. 99, Canadian Association of Physicists Congress (CAP Congress 2009), Moncton, Canada, 7 Jun 2009 – 10 Jun 2009.

9 Jun 2009, T. Stuart, J. A. Slater, F. Bussières and W. Tittel, "Budget entanglement: a compact and intrinsically stable source of polarization entangled photons" (contributed), TU-A4-2, *Physics in Canada* **65**(2):p. 85, Canadian Association of Physicists Congress (CAP Congress 2009), Moncton, Canada, 7 Jun 2009 – 10 Jun 2009.

10 Jun 2009, C. La Mela, A. Delfan, E. Saglamyurek and W. Tittel, "Photon-echo based N-path interferometers for precision measurements and quantum communication" (contributed), WE-P4-2, *Physics in Canada* **65**(2):p. 117, Canadian Association of Physicists Congress (CAP Congress 2009), Moncton, Canada, 7 Jun 2009 – 10 Jun 2009.

10 Jun 2009, M. Lobino, C. Kupchak, E. Figueroa, J. Appel and A. I. Lvovsky, "Do we need quantum light to test quantum memory?" (invited), Quantum Optics VII, Zakopane, Poland, 8 Jun 2009 – 12 Jun 2009.

10 Jun 2009, E. Saglamyurek, C. La Mela, S. A. Moiseev and W. Tittel, "Spectral tailoring of inhomogeneously broadened absorption profiles with notch-filtered light" (contributed), WE-P4-3, *Physics in Canada* **65**(2):p. 118, Canadian Association of Physicists Congress (CAP Congress 2009), Moncton, Canada, 7 Jun 2009 – 10 Jun 2009.

10 Jun 2009, B. C. Sanders, "On continuous variable quantum algorithms for oracle identification problems", Université Libre de Bruxelles, Center for Quantum Information and Communication (QuIC).

11 Jun 2009, W. Tittel, "Experimental quantum communication in the QC2Lab" (invited), QuantumWorks Annual General Meeting 2009, Toronto, Canada, 11 Jun 2009 – 12 Jun 2009.

19 Jun 2009, B. C. Sanders, N. S. Babcock, A. de la Lande and D. R. Salahub, "Electron superhighways and bridges in protein complexes", Universität Wien, Quantum Optics, Quantum Nanophysics, Quantum Information.

23 Jun 2009, B. C. Sanders, "An introduction to 'continuous variable' quantum information", Université Paris-Sud 11, Laboratoire de Recherche en Informatique (LRI).

24 Jun 2009, S. A. Moiseev and W. Tittel, "Raman-echo quantum memory" (invited), 10th International Meeting on Hole Burning, Single Molecule, and Related Spectroscopies: Science Applications (HBSM 2009), Palm Cove, Australia, 22 Jun 2009 – 27 Jun 2009.

25 Jun 2009, A. Hentschel and B. C. Sanders, "Using machine learning for measuring and controlling quantum system" (contributed), Alberta Quantum and Nano-Optics 2009 Annual Meeting (QuNO 2009), Calgary, Canada, 24 Jun 2009 – 27 Jun 2009.

25 Jun 2009, B. C. Sanders, M. Lobino, D. Korystov, C. Kupchak, E. Figueroa and A. I. Lvovsky, "Complete characterization of quantum-optical processes", Institut d'Optique – Graduate School, Groupe d'Optique Quantique.

25 Jun 2009, A. Scherer, R. B. Howard, B. C. Sanders and W. Tittel, "Quantum states prepared by real-world entanglement swapping" (contributed), Alberta Quantum and Nano-Optics 2009 Annual Meeting (QuNO 2009), Calgary, Canada, 24 Jun 2009 – 27 Jun 2009.

25 Jun 2009, Z. Shaterzadeh Yazdi, P. Xue, B. C. Sanders, L. Livadaru, J. L. Pitters, G. A. DiLabio and R. A. Wolkow, "Quantum computing with dangling bond pairs on a Si surface" (contributed), Alberta Quantum and Nano-Optics 2009 Annual Meeting (QuNO 2009), Calgary, Canada, 24 Jun 2009 – 27 Jun 2009.

26 Jun 2009, E. Saglamyurek, C. La Mela, S. A. Moiseev and W. Tittel, "Spectral tailoring of inhomogeneously broadened absorption profiles with notch-filtered light" (contributed), Alberta Quantum and Nano-Optics 2009 Annual Meeting (QuNO 2009), Calgary, Canada, 24 Jun 2009 – 27 Jun 2009.

26 Jun 2009, N. Sinclair, E. Saglamyurek, C. La Mela and W. Tittel, "Tm:$LiNbO_3$ waveguides: a novel material candidate for quantum memories" (contributed), Alberta Quantum and Nano-Optics 2009 Annual Meeting (QuNO 2009), Calgary, Canada, 24 Jun 2009 – 27 Jun 2009.

26 Jun 2009, A. Delfan, E. Saglamyurek, C. La Mela and W. Tittel, "Photon-echo based quantum memory and state transformation" (poster), 10th International Meeting on Hole Burning, Single Molecule, and Related Spectroscopies: Science Applications (HBSM 2009), Palm Cove, Australia, 22 Jun 2009 – 27 Jun 2009.

6 Jul 2009, A. I. Lvovsky, "Making and measuring quantum

states of light" (invited), South African Institute of Physics 2009 Winter School on Quantum Information Processing and Communication, Durban, South Africa, 6 Jul 2009.

7 Jul 2009, J.-S. Corbeil, J. A. Slater, G. Bouwmans, S. Virally, F. Bussières, S. Lacroix, N. Godbout and W. Tittel, "Photons Annoncés Générés dans une Fibre Microstructurée" (invited, refereed), Journées Nationales d'Optique Guidée (JNOG 2009), Lille, France, 6 Jul 2009 – 9 Jul 2009.

8 Jul 2009, M. Lobino, C. Kupchak, E. Figueroa, J. Appel and A. I. Lvovsky, "A peek into a quantum black box" (plenary), The 54th Annual conference of the South African Institute of Physics, Durban, South Africa, 6 Jul 2009 – 10 Jul 2009.

13 Jul 2009, S. A. Moiseev, A. A. Kamli and B. C. Sanders, "Coherent control of low loss surface polaritons" (contributed), International Laser Physics Workshop (LPHYS'09), Barcelona, Spain, 13 Jul 2009 – 17 Jul 2009.

14 Jul 2009, A. Delfan, E. Saglamyurek, C. La Mela and W. Tittel, "Interferometry using photon-echoes for precision measurements and quantum communication" (invited), International Laser Physics Workshop (LPHYS'09), Barcelona, Spain, 13 Jul 2009 – 17 Jul 2009.

15 Jul 2009, C. Kupchak, M. Lobino, E. Figueroa and A. I. Lvovsky, "Process tomography of quantum-optical memory" (invited), International Laser Physics Workshop (LPHYS'09), Barcelona, Spain, 13 Jul 2009 – 17 Jul 2009.

17 Jul 2009, N. S. Babcock, "Quantum theory at MoNo" (invited), Motion Notion, Drayton Valley, Canada, 16 Jul 2009 – 19 Jul 2009 (A two-part beachfront lecture series on quantum physics).

19 Jul 2009, B. C. Sanders, P. Xue, Z. Shaterzadeh Yazdi, J. L. Pitters, G. A. DiLabio, L. Livadaru and R. A. Wolkow, "Quantum computing with dangling bonds on a silicon surface" (invited), International Conference on Quantum Foundation and Technology: Frontier and Future (ICQFT '09), Shanghai, People's Republic of China, 17 Jul 2009 – 22 Jul 2009.

19 Jul 2009, P. Xue, B. C. Sanders, A. Blais, K. Lalumière and D. Leibfried, "Implementing quantum walks" (contributed), International Conference on Quantum Foundation and Technology: Frontier and Future (ICQFT '09), Shanghai, People's Republic of China, 17 Jul 2009 – 22 Jul 2009.

20 Jul 2009, A. I. Lvovsky, "Characterization of memory for light as a quantum-optical process" (invited), International Conference on Quantum Foundation and Technology: Frontier and Future (ICQFT '09), Shanghai, People's Republic of China, 17 Jul 2009 – 22 Jul 2009.

22 Jul 2009, A. I. Lvovsky, "Making light, photon by photon", East China Normal University, Department of Physics.

30 Jul 2009, G. Brassard, G. Berlin, F. Bussières, N. Godbout, J. A. Slater and W. Tittel, "Flipping quantum coins" (invited), Classical and Quantum Information Assurance Foundations and Practice (Dagstuhl Seminars), Wadern, Germany, 26 Jul 2009 – 31 Jul 2009.

30 Jul 2009, F. Bussières, J. A. Slater, J. Jin, N. Godbout and W. Tittel, "Measuring entanglement with universal time-bin qubit analyzers" (invited), Classical and Quantum Information Assurance Foundations and Practice (Dagstuhl Seminars), Wadern, Germany, 26 Jul 2009 – 31 Jul 2009.

4 Aug 2009, F. Bussières, J. A. Slater, J. Jin, N. Godbout, S. Hosier and W. Tittel, "Convertible quantum encodings and hybrid entanglement on a real-world fiber link" (contributed), SPIE Quantum Communications and Quantum Imaging VII (QCQI 2009), San Diego, United States of America, 2 Aug 2009 - 6 Aug 2009.

5 Aug 2009, X. F. Mo, I. Lucio Martinez, P. Chan, S. Hosier and W. Tittel, "Proof-of-principle demonstration of quantum key distribution with quantum frames" (contributed), SPIE Quantum Communications and Quantum Imaging VII (QCQI 2009), San Diego, United States of America, 2 Aug 2009 – 6 Aug 2009.

6 Aug 2009, A. MacRae, G. Campbell, A. Ordog and A. I. Lvovsky, "Double electromagnetically induced transparency in rubidium vapour" (invited), SPIE Quantum Communications and Quantum Imaging VII (QCQI 2009), San Diego, United States of America, 2 Aug 2009 – 6 Aug 2009.

11 Aug 2009, J. Joo and D. L. Feder, "Error-correcting one-way quantum computation with global entangling gates", National University of Singapore, Centre for Quantum Technologies.

17 Aug 2009, P. Chan, I. Lucio Martinez, X. F. Mo, S. Hosier and W. Tittel, "Quantum key distribution at the University of Calgary" (contributed), Summer School on Communications and Information Theory, Banff, Canada, 17 Aug 2009 – 19 Aug 2009.

17 Aug 2009, J. S. Kim, "Renyi entropy and entanglement constraint in multipartite quantum system", Seoul National University, Department of Mathematical Science.

19 Aug 2009, J. Joo and D. L. Feder, "Error-correcting one-way quantum computation with global entangling gates" (invited), Korean Institute of Advanced Studies Workshop on Quantum Information Sciences, Seoul, Republic of Korea, 17 Aug 2009 – 21 Aug 2009.

19 Aug 2009, Z. Shaterzadeh Yazdi, "Quantum computing with dangling bond pairs on a Si surface", University of Calgary, Institute for Quantum Information Science.

20 Aug 2009, F. Buscemi, G. Gour and J. S. Kim, "Polygamy of distributed entanglement" (invited), Korean Institute of Advanced Studies Workshop on Quantum Information Sciences, Seoul, Republic of Korea, 17 Aug 2009 – 21 Aug 2009.

20 Aug 2009, W. Tittel, "Quantum communication in the QC2 Lab" (invited), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

21 Aug 2009, A. Hentschel and B. C. Sanders, "Machine learning for adaptive quantum measurement" (poster), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

21 Aug 2009, S. Rahimi-Keshari, A. Mann, A. Scherer and B. C. Sanders, "Analytical results for coherent state quantum process tomography" (poster), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

21 Aug 2009, A. Scherer, B. C. Sanders and W. Tittel, "Quantum states prepared by real-world entanglement swapping and implications for quantum key distribution" (poster), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

21 Aug 2009, Z. Shaterzadeh Yazdi, P. Xue, B. C. Sanders, L. Livadaru, J. L. Pitters, G. A. DiLabio and R. A. Wolkow, "Quantum computing with dangling bond pairs on a silicon surface" (poster), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

21 Aug 2009, G. Berlin, G. Brassard, F. Bussières, N. Godbout, J. A. Slater and W. Tittel, "Flipping quantum coins" (poster, contributed), 2009 *i*CORE Banff Informatics Summit (*i*CORE Summit 2009), Banff, Canada, 20 Aug 2009 – 22 Aug 2009.

23 Aug 2009, B. Toloui Semnani, G. Gour and B. C. Sanders, "Frameness of formation for a qubit", Canadian Quantum Information Student Conference (CQISC 2009), Toronto, Canada, 22 Aug 2009 – 23 Aug 2009.

24 Aug 2009, C. Simon, N. Sangouard, H. de Riedmatten, M. Afzelius, N. Gisin, M. U. Staudt, J. Minar, H. Zbinden, B. Zhao, Y.-A. Chen, J.-W. Pan and R. Dubessy, "Quantum repeaters" (contributed), Conference on Quantum Information and Quantum Control (CQIQC - III), Toronto, Canada, 24 Aug 2009 – 27 Aug 2009.

25 Aug 2009, F. Bussières, G. Berlin, G. Brassard, N. Godbout, J. A. Slater and W. Tittel, "Flipping quantum coins" (contributed), Conference on Quantum Information and Quantum Control (CQIQC - III), Toronto, Canada, 24 Aug 2009 – 27 Aug 2009.

25 Aug 2009, A. Hentschel and B. C. Sanders, "Machine learning for adaptive quantum measurement" (poster), Conference on Quantum Information and Quantum Control (CQIQC - III), Toronto, Canada, 24 Aug 2009 – 27 Aug 2009.

26 Aug 2009, J. S. Kim, A. Das and B. C. Sanders, "Entanglement monogamy of multipartite higher-dimensional quantum systems using convex-roof extended negativity" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

26 Aug 2009, F. Buscemi, G. Gour and J. S. Kim, "Polygamy of distributed entanglement" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

26 Aug 2009, J. S. Kim, "Polygamy of entanglement in multipartite quantum systems" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

26 Aug 2009, N. Wiebe, D. W. Berry, P. Høyer and B. C. Sanders, "Quantum computer simulations of time dependent hamiltonians" (contributed), Conference on Quantum Information and Quantum Control (CQIQC - III), Toronto, Canada, 24 Aug 2009 – 27 Aug 2009.

27 Aug 2009, J. S. Kim and B. C. Sanders, "On the geomatic distance between quantum states with positive partial transposition and private states" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

27 Aug 2009, X. F. Mo, I. Lucio Martinez, P. Chan, S. Hosier and W. Tittel, "Quantum key distribution with quantum frames" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

27 Aug 2009, W. Tittel, "Photon-Echo quantum memory and controlled state manipulation" (invited), Conference on Quantum Information and Quantum Control (CQIQC - III), Toronto, Canada, 24 Aug 2009 – 27 Aug 2009.

27 Aug 2009, P. Xue, B. C. Sanders and D. Leibfried, "Quantum walk on a line for a trapped ion" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

28 Aug 2009, A. I. Lvovsky, "Making light out of photons", University of Gdañsk, Department of Physics.

29 Aug 2009, Y. J. Wang, B. C. Sanders, B.-M. Bai and X. M. Wang, "Feedback iterative decoding of sparse quantum codes" (contributed), The 9th Asian Conference on Quantum Information Science (AQIS 2009), Nanjing, People's Republic of China, 26 Aug 2009 – 29 Aug 2009.

1 Sep 2009, N. S. Babcock, "Quantum theory at MathCamp 2009" (invited), Burning Man, Black Rock City, United States of America, 31 Aug 2009 – 7 Sep 2009 (A three-part lecture series on quantum physics).

8 Sep 2009, S. Virally, J.-S. Corbeil, J. A. Slater, A. Kudlinski, G. Bouwmans, L. Labonté, F. Bussières, M. Leduc, W. Tittel, N. Godbout and S. Lacroix, "Fibres microstructurées pour la conception de sources non classiques de photons" (poster, contributed), 11ème édition du Colloque sur les Lasers et l'Optique Quantique (COLOQ'11), Mouans-Sartoux, France, 7 Sep 2009 – 9 Sep 2009.

22 Sep 2009, C. Simon, "Towards practical quantum repeaters (and quantum experiments with human eye detectors)" (invited), Quantum Information Processing and Computation

(QIPC 2009), Rome, Italy, 21 Sep 2009 – 25 Sep 2009.

9 Oct 2009, D. L. Feder, "Are fermions useful for quantum computation?", Simon Fraser University, Department of Physics.

9 Oct 2009, B. C. Sanders, "Machine learning for precise quantum measurement", Massachusetts Institute of Technology, Quantum Information Science @ MIT.

19 Oct 2009, N. Wiebe, D. W. Berry, P. Høyer and B. C. Sanders, "Higher order decompositions of ordered operator exponentials" (invited), International Workshop on Quantum Nonstationary Systems (IWQNS 2009), Brasilia, Brazil, 19 Oct 2009 – 23 Oct 2009.

28 Oct 2009, G. Berlin, G. Brassard, F. Bussières, N. Godbout, J. A. Slater and W. Tittel, "Flipping quantum coins" (contributed, refereed), International Conference on Quantum Communication and Quantum Networking (ICQCQN 2009), Naples, Italy, 26 Oct 2009 – 30 Oct 2009.

28 Oct 2009, A. Delfan, E. Saglamyurek, C. La Mela and W. Tittel, "Quantum state manipulation using photon-echo type atom-light interaction" (invited), International Conference on Quantum Communication and Quantum Networking (ICQCQN 2009), Naples, Italy, 26 Oct 2009 – 30 Oct 2009.

3 Nov 2009, A. I. Lvovsky, "Peeking into quantum black boxes", Imperial College London, Institute for Mathematical Sciences.

6 Nov 2009, G. Berlin, G. Brassard, F. Bussières, N. Godbout, J. Jin, J. A. Slater and W. Tittel, "Measuring entanglement with universal time-bin qubit analyzers" (invited), Single Photon Workshop 2009 (SPW 2009), Boulder, United States of America, 3 Nov 2009 – 6 Nov 2009.

10 Nov 2009, S. Lee, J. S. Kim and B. C. Sanders, "Distribution and dynamics of entanglement", Seoul National University, Department of Mathematical Sciences.

13 Nov 2009, B. C. Sanders, "Monogamy and polygamy of entanglement for qudit" (plenary), International Conference on Mathematics and Information Security (ICMIS 2009), Sohag, Egypt, 13 Nov 2009 – 15 Nov 2009.

18 Nov 2009, B. C. Sanders, "How to build a quantum computer and what to do with it?", The University of Nottingham, School of Mathematical Sciences.

20 Nov 2009, A. Hentschel and B. C. Sanders, "Machine learning for adaptive quantum measurement", University of Alberta, Alberta Ingenuity Centre for Machine Learning, Department of Computing Science.

20 Nov 2009, B. C. Sanders, "Machine learning for precise quantum measurement", University of Oxford, Department of Physics.

2 Dec 2009, B. C. Sanders, "Machine learning for precise quantum measurement" (invited), International Conference on Quantum Information and Technology (ICQIT 2009), Tokyo, Japan, 2 Dec 2009 – 5 Dec 2009.

3 Dec 2009, P. Xue, B. C. Sanders and D. Leibfried, "Quantum walk on a line for a trapped ion" (poster), International Conference on Quantum Information and Technology (ICQIT 2009), Tokyo, Japan, 2 Dec 2009 – 5 Dec 2009.

11 Jan 2010, G. Gour, "Basic quantum information protocols" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

11 Jan 2010, G. Gour, "Entanglement quantification and manipulation" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

12 Jan 2010, G. Gour, "Quantum channels" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

12 Jan 2010, G. Gour, "Quantum resource theories" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

13 Jan 2010, W. Tittel, "Quantum cryptography", University of Calgary, Institute for Quantum Information Science.

22 Jan 2010, B. C. Sanders, "Implementations of quantum information I" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

23 Jan 2010, B. C. Sanders, "Implementations of quantum information II" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

27 Jan 2010, B. C. Sanders, "Machine learning for quantum measurement" (invited), International Program on Quantum Information 2010 (IPQI-2010), Bhubaneswar, India, 3 Jan 2010 – 30 Jan 2010.

1 Feb 2010, D. L. Feder, "Measurement-based quantum computing in a fermionic ground state", University of British Columbia, Department of Physics and Astronomy.

19 Feb 2010, B. Toloui Semnani, G. Gour and B. C. Sanders, "Mixed state quantum reference frame resources" (poster), Southwest Quantum Information and Technology Twelfth Annual Meeting (SQuInT 2010), Santa Fe, United States of America, 18 Feb 2010 – 21 Feb 2010.

20 Feb 2010, B. Fortescue, A. Keet, B. C. Sanders and D. Markham, "Quantum secret sharing with qudit graph states" (contributed), Southwest Quantum Information and Technology Twelfth Annual Meeting (SQuInT 2010), Santa Fe, United States of America, 18 Feb 2010 – 21 Feb 2010.

20 Feb 2010, A. Scherer, B. C. Sanders and W. Tittel, "Mathematical model for real-world entanglement swapping and applications to practical long-distance quantum key distribution" (contributed), Southwest Quantum Information and Technology Twelfth Annual Meeting (SQuInT 2010), Santa Fe, United States of America, 18 Feb 2010 – 21 Feb

2010.

24 Feb 2010, A. A. Kamli, B. C. Sanders and S. A. Moiseev, "Low loss surface polaritons and quantum memory in meta-materials", 2nd International Conference on Metamaterials, Photonic Crystals and Plasmonics (META'10), Cairo, Egypt, 22 Feb 2010 – 25 Feb 2010.

1 Mar 2010, A. I. Lvovsky, "Making, storing and measuring light: photon by photon", University of Ulm, Department of Physics.

5 Mar 2010, B. C. Sanders, "Machine learning for precise quantum measurements" (plenary), International Scientific Spring – 2010, Islamabad, Islamic Republic of Pakistan, 1 Mar 2010 – 6 Mar 2010.

15 Mar 2010, M. S. Underwood and D. L. Feder, "Quantum walks in momentum space", Bulletin of the American Physical Society **55**(2): A26.00008, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.A26.8).

16 Mar 2010, Z. Shaterzadeh Yazdi and B. C. Sanders, "Extended Hubbard model simulations of charge-qubit circuits: from idealism to realism", Bulletin of the American Physical Society **55**(2): L26.00012, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.L26.12).

17 Mar 2010, J. Joo and D. L. Feder, "Concatenated logical cluster state using 5-qubit QECC" (contributed), Bulletin of the American Physical Society **55**(2): Q26.00008, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.Q26.8).

18 Mar 2010, A. G. D'Souza and D. L. Feder, "Fermionic resources for quantum teleportation", Bulletin of the American Physical Society **55**(2): W26.00012, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.W26.12).

18 Mar 2010, D. L. Feder and G. Shlyapnkov, "Quantum computation in the ground state of interacting fermions", Bulletin of the American Physical Society **55**(2): W26.00013, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.W26.13).

19 Mar 2010, J. Bourassa, J. Joo, A. Blais and B. C. Sanders, "Electromagnetically induced transparency combined with lasing without inversion in superconducting circuits" (contributed), Bulletin of the American Physical Society **55**(2): Z26.00009, APS March Meeting 2010 (APS March 2010), Portland, United States of America, 15 Mar 2010 – 19 Mar 2010 (http://meetings.aps.org/link/BAPS.2010.MAR.Z26.9).

21 Mar 2010, E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler, "Integrated quantum memory for quantum communication" (invited), Workshop on Crytography from Storage Imperfections, Pasadena, United States of America, 20 Mar 2010 – 22 Mar 2010.

23 Mar 2010, W. Tittel, "Quantum communication with optical fiber (tutorial)" (invited), OFC/NFOEC2010, San Diego, United States of America, 21 Mar 2010 – 25 Mar 2010.

24 Mar 2010, E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler, "Integrated quantum memory for quantum communication" (invited), OFC/NFOEC2010, San Diego, United States of America, 21 Mar 2010 – 25 Mar 2010.

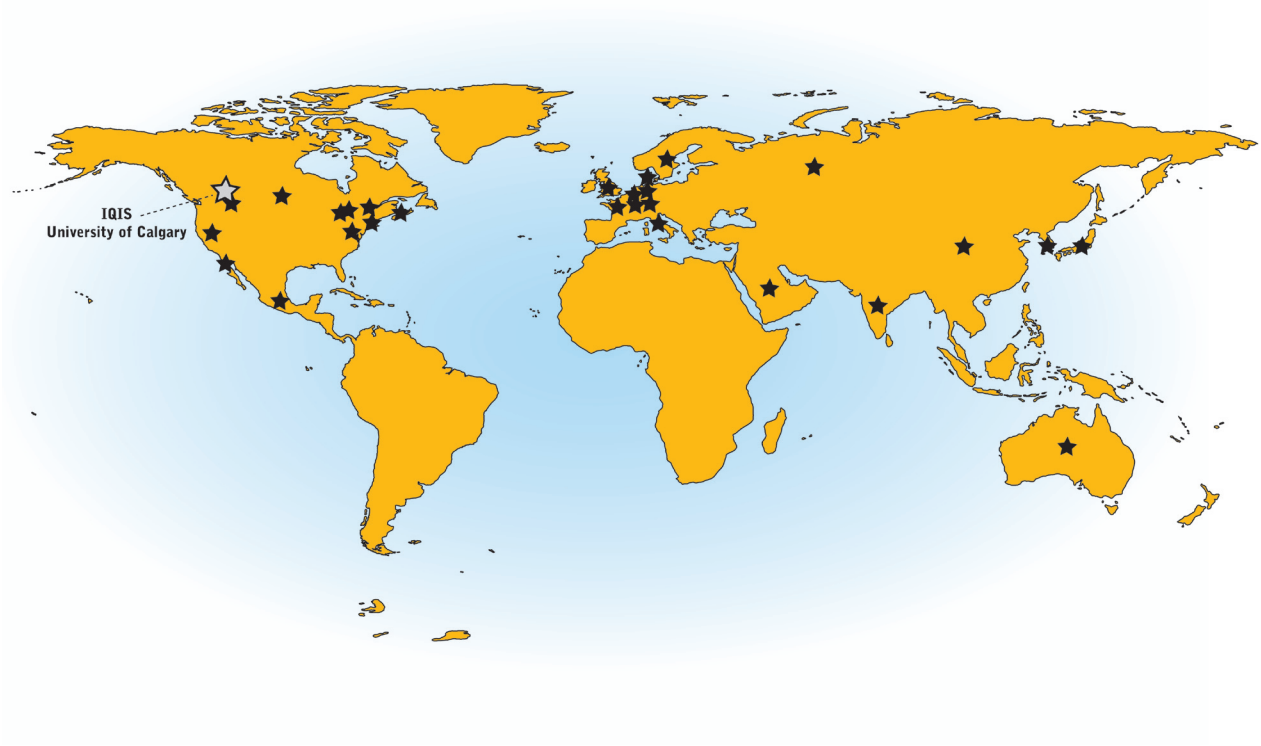
31 Mar 2010, A. Scherer, B. C. Sanders and W. Tittel, "Mathematical model for real-world entanglement swapping and applications to long-distance quantum key distribution", Laboratoire Traitement et Communication de l'Information CNRS - Télécom ParisTech Network and Computer Science Department.

31 Mar 2010, E. Saglamyurek, N. Sinclair, C. La Mela, W. Tittel, M. George, R. Ricken and W. Sohler, "Integrated quantum memory for quantum communication", Lund University, Division of Atomic Physics.

9. Collaborations

Institution	Location
Australian National University	Canberra, Australia
China Southeast University	Nanjing, People's Republic of China
Chonnam National University	Gwangju, Republic of Korea
Copenhagen University	Copenhagen, Kingdom of Denmark
East China Normal University	Shanghai, People's Republic of China
École Normale Supérieure	Paris, France
École Polytechnique Montréal	Montréal, Canada
Griffith University	Brisbane, Australia
Imperial College London	London, United Kingdom
Indian Institute of Science Bangalore	Bangalore, India
Indian Institute of Technology Powai	Mumbai, India
Kazan Physical-Technical Institute of the Russian Academy of Science	Kazan, Russian Federation
King Khalid University	Abha, Kingdom of Saudi Arabia
Laboratoire Aimé Cotton	Paris, France
Lund University	Lund, Kingdom of Sweden
Massachusetts Institute of Technology	Cambridge, United States of America
Max Planck Institute for Quantum Optics	Garching, Federal Republic of Germany
Max Planck Institute for the Science of Light	Erlangen, Federal Republic of Germany
Montana State University	Bozeman, United States of America
National Institute of Standards and Technology	Boulder, United States of America
Pirelli Labs	Milano, Italy
Power Wind GmBH	Hamburg, Federal Republic of Germany
Southern Alberta Institute of Technology	Calgary, Canada
St. Francis Xavier University	Antigonish, Canada
Universität Bonn	Bonn, Federal Republic of Germany
Université Lille 1	Villeneuve d'Ascq Cédex, France
University of California at Berkeley	Berkeley, United States of America
Université de Genève	Genève, Switzerland
University of Manitoba	Winnipeg, Canada
Université de Montréal	Montréal, Canada
University of Nagoya	Nagoya, Japan
University of New South Wales	Canberra, Australia
Universität Paderborn	Paderborn, Federal Republic of Germany
University of Southern California	Los Angeles, United States of America
University of Tokyo	Tokyo, Japan
University of Toronto	Toronto, Canada
University of Twente	Enschede, The Netherlands
Wilfrid Laurier University	Waterloo, Canada

MAP OVERLAY OF COLLABORATION WITH IQIS



10. Visitors

Name	Dates of Visit	Home Institution
Félix Bussières	16 Jan 2007 – 31 Dec 2009	Université de Montréal, Canada
Yunjiang Wang	15 Sep 2008 – 30 Apr 2010	Xidian University, Xian, People's Republic of China
Michele Mosca	3 Apr 2009	University of Waterloo, Canada
Herschel Rabitz	4 – 8 Apr 2009	Princeton University, United States of America
Christoph Simon	20 – 23 Apr 2009	Université de Genève, Switzerland
Yi Zhao	21 – 22 Apr 2009	University of Toronto, Canada
Xiongfeng Ma	24 Apr – 6 May 2009	University of Waterloo, Canada
Loïck Magnin	1 May – 31 Aug 2009	Université Paris-Sud 11, France
John Sipe	5 – 6 May 2009	University of Toronto, Canada
Abhay Shankar Shastry	7 May – 15 Jul 2009	Indian Institute of Techonology – Kharagpur, India
Ben Lanyon	21 – 23 May 2009	University of Queensland, Brisbane, Australia
Ady Mann	25 Jun – 21 Aug 2009	Technion – Israel Institute of Technology, Israel
Geshon Kurizki	25 Jul – 1 Aug 2009	Weizmann Institute of Science, Rehovot, Israel
Andrew Landahl	6 – 10 Aug 2009	Sandia National Laboratories, Albuquerque, United States of America
Andrew Forbes	10 – 11 Aug 2009	CSIR National Laser Centre, Pretoria, South Africa
Stef Roux	10 – 11 Aug 2009	CSIR National Laser Centre, Pretoria, South Africa
Iman Marvian	25 Aug – 19 Sep 2009	University of Waterloo, Canada
Dominic Berry	31 Aug – 11 Sep 2009	University of Waterloo, Canada

Name	Dates of Visit	Home Institution
Mohan Sarovar	10 Sep 2009	University of California at Berkeley, United States of America
Piotr Kolenderski	11 – 17 Sep 2009	Nicolaus Copernicus University, Torun, Poland
Ranjeet Kumar	15 Sep 2009 – 31 Aug 2010	Indian Institute of Technology – Delhi, India
Ali Rezakhani	15 – 28 Sep 2009	University of Southern California, United States of America
Paul Barclay	30 Sep – 1 Oct 2009	Hewett-Packard Labs, Palo Alto, United States of America
Nathan Killoran	5 – 7 Oct 2009	University of Waterloo, Canada
Yang Han	13 Oct 2009 – 30 Sep 2010	National University of Defence Technology of China, Changsha, People's Republic of China
Peng Xue	14 Oct – 30 Nov 2009	China Southeast University, Nanjing, People's Republic of China
Michel Pioro-Ladrière	26 Oct 2009	Université de Sherbrooke, Canada
Rainer Blatt	2 Nov 2009	Universität Innsbruck, Austria
Steve Flammia	2 – 7 Nov 2009	Perimeter Institute for Theoretical Physics, Waterloo, Canada
Saurya Das	18 – 19 Nov 2009	University of Lethbridge, Canada
Stephen Bartlett	24 – 26 Nov 2009	University of Sydney, Australia
Eugene Polzik	7 – 10 Dec 2009	Copenhagen University, Kingdom of Denmark
Marcos Cesar de Oliveira	29 Jan – 12 Feb 2010	Universidade Estadual de Campinas, São Paulo, Brazil
Morgan Hedges	29 Jan – 3 Feb 2010	Australian National University, Canberra, Australia
Arnaud Rispe	1 Feb – 31 Jul 2010	École Normale Supérieure, Paris, France
Howard Carmichael	18 – 19 Feb 2010	University of Auckland, New Zealand
Hipolito Garcia-Gracia	1 Mar 2010 – 28 Feb 2011	Tecnologico de Monterrey, Mexico
Jobez Pierre	1 Mar – 31 Aug 2010	École Normale Supérieure Paris, France
Andrew Childs	9 – 11 Mar 2010	University of Waterloo, Canada
Rufus Cone	18 – 20 Mar 2010	Montana State University, Bozeman, United States of America
Charles Thiel	18 – 20 Mar 2010	Montana State University, Bozeman, United States of America
Michael Förtsch	29 Mar – 29 Jul 2010	Universtät Erlangen-Nürnberg, Erlangen, Germany

B. Teaching, Training and Education

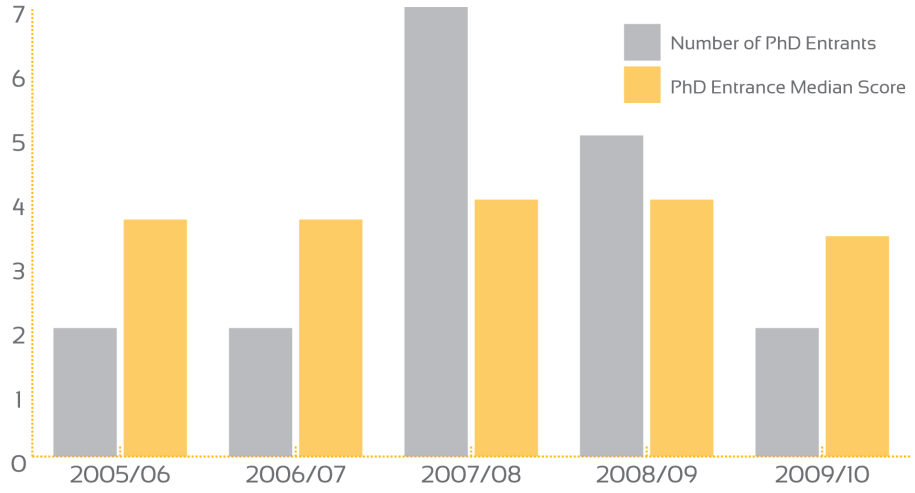
1. Undergraduate projects and supervision

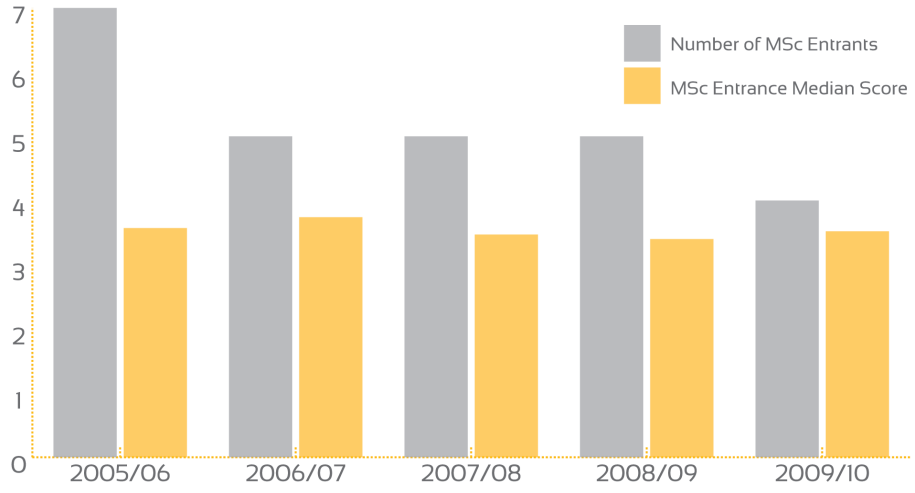
Name	Name of Project	Supervisor
Thomas Apperley	A neutral atom SQUID (PHYS 598)	D. Feder
Benjamin Blumer	Widgets for universal quantum computation using quantum walk (PHYS 599)	D. Feder
Robin Hunter	Traversing weighted graphs with quantum walks (PHYS 598)	D. Feder
Ranjeet Kumar	Process tomography of fundamental quantum optical operators (visiting student)	A. I. Lvovsky
Jobez Pierre	Gradient echo memory for light in rubidium vapor (visiting student)	A. I. Lvovsky
Brittany Welsh	Construction of a tapered diode amplifier (NSERC USRA)	A. I. Lvovsky
Adrian Keet	Quantum secret sharing with qudit states (NSERC USRA)	B. C. Sanders
Adrian Keet	Simulating quantum walks for universal quantum computation (PHYS 598)	B. C. Sanders
Michelle Liu	Analysis of 4 side channel attacks in BB84 systems (PHYS 599)	B. C. Sanders
Abhay Shankar Shastry	Machine learning for quantum measurements (visiting student)	B. C. Sanders
Thomas Apperley	Laser stabilization for quantum memory (NSERC USRA)	W. Tittel
Sean Blancher	Single photon detectors (NSERC USRA)	W. Tittel

2. Quantum information graduate courses

Course Name	Instructor	Description
CPSC 511 Complexity Theory (co-taught with CPSC 611)	P. Høyer	Time and space complexity; the classes P, LOGSPACE, PSPACE and their nondeterministic counterparts; containments and separations between complexity classes; intractability and the theory of NP-completeness; complexity theories for probabilistic algorithms and for parallel algorithms.
CPSC 519 Quantum Computation (co-taught with CPSC 619)	P. Høyer	Quantum information, quantum algorithms including Shor's quantum factoring algorithm and Grover's quantum searching technique, quantum error correcting codes, quantum cryptography, nonlocality and quantum communication complexity, and quantum computational complexity.
CPSC 611 Complexity Theory	P. Høyer	Deterministic and non-deterministic time and space complexity; complexity classes and hierarchies; NP-complete problems and intractable problems; axiomatic complexity theory.
CPSC 619 Quantum Computation	P. Høyer	Quantum information, quantum algorithms including Shor's quantum factoring algorithm and Grover's quantum searching technique, quantum error correcting codes, quantum cryptography, nonlocality and quantum communication complexity, and quantum computational complexity.
PHYS 677 Implementation of Quantum Information	B. C. Sanders	Proposals and realizations of quantum information tasks including quantum computation, quantum communication, and quantum cryptography in optical, atomic, molecular, and solid state systems.
PHYS 615 Advanced Quantum Mechanics I	C. Simon	Review of special relativity, electrodynamics, and nonrelativistic quantum mechanics. Klein-Gordon and Dirac equations with minimal coupling. Antimatter and the PCT Theorem. Foldy-Wouthuysen transformation and relativistic corrections to Hydrogen spectroscopy. Introduction to quantum field theory. (Formerly: Basic formalism of the theory and its interpretation, symmetry generators. Scattering theory. Bound states. Charged particles in electric and magnetic fields. Approximation methods.)

3. Graduate students: enrolments and quality of entrants





4. Summer schools and student conferences

None.

C. Services and Outreach

1. Conference committees

Member(s)	Committee	Conference/Workshop/ Award	Location	Conference Dates
A. I. Lvovsky	Member, Quantum Optics Subcommittee	International Quantum Electronics Conference (IQEC)	Baltimore, United States of America	31 May – 5 Jun 2009
A. I. Lvovsky	Member, International Advisory Committee	The Eleventh International Conference on Squeezed States and Uncertainty Relations (ICSSUR 2009)	Olomouc, Czech Republic	22 – 26 Jun 2009
A. I. Lvovsky	Member, Program Committee	The Fourth International Conference on Quantum, Nano, and Micro Technology (ICQNM 2010)	St. Maarten, The Netherlands	10 – 15 Feb 2010
P. Høyer	Member, Program Committee	The Fifth Conference on the Theory of Quantum Computation, Communication and Cryptography	Leeds, United Kingdom	13 – 15 Apr 2010
B. C. Sanders	Member, Program Committee	IEEE Congress on Evolutionary Computation (CEC 2009)	Trondheim, Norway	18 – 21 May 2009
B. C. Sanders	Member, Program Committee	Quantum Communications and Quantum Imaging VII, SPIE Optics and Photonics (QCQI 2009)	San Diego, United States of America	2 – 6 Aug 2009
B. C. Sanders	Member, Program Committee	The Fourth International Conference on Quantum, Nano, and Micro Technologies (ICQNM 2010)	St. Maarten, The Netherlands	10 – 15 Feb 2010
B. C. Sanders	Member, Organizing Committee	The Tenth Canadian Summer School on Quantum Information (QI10)	Vancouver, Canada	17 – 30 Jul 2010
B. C. Sanders	Member, Organizing Committee	Workshop on Quantum Algorithms, Computational Models, and Foundations on Quantum Mechanics (QAMF)	Vancouver, Canada	23 – 25 Jul 2010
B. C. Sanders	Member, International Advisory Committee	Group XXVII Symposium (Group XXVIII 2010)	Newcastle, United Kingdom	26 – 30 Jul 2010
B. C. Sanders	Member, International Scientific Organizing Committee	International Conference on Quantum Information and Computation	Stockholm, Sweden	4 – 8 Oct 2010

Member(s)	Committee	Conference/Workshop/ Award	Location	Conference Dates
B. C. Sanders	Member, Program Committee	2011 Canadian Association of Physicists Congress	St. Johns, Canada	13 – 17 Jun 2011
B. C. Sanders	Co-Chair	2012 Canadian Association of Physicists Congress	Calgary, Canada	TBA
W. Tittel	Member, Program Committee	The Second Workshop on Theory and Realisation of Practical Quantum Key Distribution	Waterloo, Canada	14 – 17 Jun 2010

2. Professional services

Name	Role	Journal/Society/Institution
D. Feder	Member, Advisory Board of Development of New Textbook	Pearson Publishing
B. C. Sanders	Member, Advisory Committee on Physics Education	American Institute of Physics
B. C. Sanders	Vice Chair, Division of Atomic and Molecular Physics and Photon Interactions	Canadian Association of Physicists
B. C. Sanders	Evaluator, FET Proactive, FP7 Call 4, QI-FT Quantum Information Foundations and Technologies	European Commission
B. C. Sanders	Reviewer, Future & Emerging Technologies — Integrated Project (QAP)	European Commission
B. C. Sanders	Reviewer, Peer Evaluation for ERC Scientific Council	European Research Council
B. C. Sanders	Expert Assessor, Industrial Technologies Office (ITO)	Industry Canada
B. C. Sanders	Panel Member, Physical Sciences for the NRC Research Associateship Program 2010	National Research Council: Policy and Global Affairs Division
B. C. Sanders	Member, NSERC Physics Evaluation Group (1505)	Natural Sciences and Engineering Research Council of Canada
B. C. Sanders	Panel Member	National Science Foundation
B. C. Sanders	Project Leader, Quantum Information Processing	Networks of Centres of Excellence for Mathematics of Information Technology and Complex Systems
B. C. Sanders	Reviewer	Networks of Centres of Excellence for Mathematics of Information Technology and Complex Systems
B. C. Sanders	Consultant, Appraisals Committee for the MMath/PhD Program in Applied Mathematics at the University of Waterloo	Ontario Council on Graduate Studies
B. C. Sanders	Member, Advisory Board	*Optics Communications*

Name	Role	Journal/Society/Institution
B. C. Sanders	Faculty Advisor	Optical Society of America University of Calgary Student Chapter
B. C. Sanders	Group Leader, Quantum Optical Science and Technology Group	Optical Society of America
B. C. Sanders	Principal Coordinator, Collaborative Research Group for Mathematics of Quantum Information	Pacific Institute for the Mathematical Sciences
B. C. Sanders	Member, Scientific Review Panel	Pacific Institute for the Mathematical Sciences
B. C. Sanders	Member, Advisory Committee	Pacific Institute for the Mathematical Sciences University of Calgary Steering Committee
B. C. Sanders	Group Leader, Theme B	QuantumWorks NSERC Innovation Platform
B. C. Sanders	Member: Research Management Committee	QuantumWorks NSERC Innovation Platform
B. C. Sanders	Member, Advisory Editorial Board	*Applied Mathematics and Information Sciences*
B. C. Sanders	Member, Editorial Board	*Physical Review A*
B. C. Sanders	Member, Editorial Board	*New Journal of Physics*
B. C. Sanders	Member, Academic Program Committee, Faculty of Graduate Studies	University of Calgary
W. Tittel	Member	International Space-QUEST (Quantum Entanglement for Space Experiments)

3. Appearances in the media

Source	Title of Article	Location	Date
Radio Canada International	What the bleep is quantum computation: Barry Sanders		21 Apr 2009
UToday	Defending information security: Barry Sanders, Wolfgang Tittel	online	9 Feb 2010
Azom.com	Scientists successfully create quantum states of light: Alex Lvovsky, Andrew MacRae	online	14 Feb 2010
Azonano.com	Researchers use quantum entanglement to stack light particles	online	14 Feb 2010
Nanowerk.com	Physicists construct quantum toy houses: Alex Lvovsky	online	14 Feb 2010
Physorg.com	Using quantum entanglement to stack light particles: Physicists play lego with photons: Alex Lvovsky, Andrew MacRae	online	14 Feb 2010
Scienceblog.com	Defending information security: Andrew MacRae, Alexander Lvovsky	online	14 Feb 2010
Dailyindia.com	Physicists construct quantum toy houses: Alex Lvovsky	online	15 Feb 2010
Greenbang.com	Light particles, tamed lego-style, could enable faster computers: Alex Lvovksy, Andrew MacRae	online	15 Feb 2010
Innovations-report.com	Physicists construct quantum toy houses: Alex Lvovsky, Andrew MacRae	online	15 Feb 2010
Newstrackindia.com	Physicists construct quantum toy houses: Alex Lvovsky	online	15 Feb 2010

Source	Title of Article	Location	Date
Redorbit.com	Physicists construct quantum toy houses: Alex Lvovsky, Andrew MacRae	online	15 Feb 2010
Scienceblog.com	Physicists construct quantum toy houses: Alex Lvovsky	online	15 Feb 2010
Sciencedaily.com	Quantum entanglement used to stack light particles	online	15 Feb 2010
Webindia123.com	Physicists construct quantum toy houses: Alex Lvovsky	online	15 Feb 2010
Yahoo.com	Physicists construct quantum toy houses: Alex Lvovsky	online	15 Feb 2010
Chemie.de	Physicists play lego with photons - University of Calgary researchers use quantum entanglement to stack light particles	online	17 Feb 2010
Physorg.com	Quantum measurement precision approaches Heisenberg limit: Alexander Hentschel, Barry Sanders	online	26 Feb 2010

4. Production

None.

5. Public lectures

None.

V FINANCES

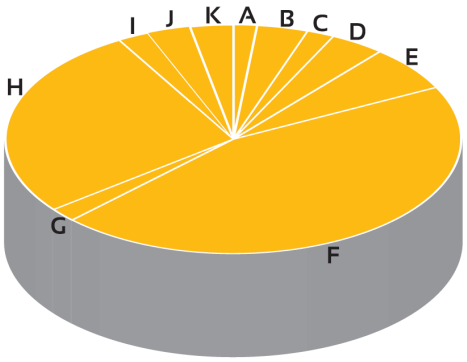
A. Operating Account: Revenue and Expenditure

Income Statement for the period 2009/2010 ending 31 March 2010			
Revenue			
	University of Calgary	$	75,000.00
	MITACS QIP Seminar Series		8,000.00
	Total Revenue	$	83,000.00
Expenditures			
	Administrative Salaries	$	62,234.83
	Benefits		8,103.33
	Office Supplies		1,522.20
	IT Support		1,327.18
	Software		23.04
	Travel and Other expense - Visitors		12,154.21
	Postage, Phone, Fax and Courier		413.05
	Printing and Engraving Services		239.76
	Special Event and Meetings		7,924.37
	IQIS Annual Report		2,452.60
	IQIS Board Meeting		5,333.41
	Maintenance		1,058.57
	MITACS QIP Seminar Series		4,000.02
	Other Expenditures		4,213.11
	Total Expenditures	$	110,999.68
Net Operating Results		**$**	**-27,999.68**

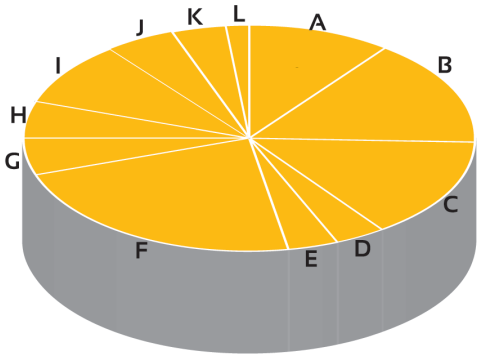
B. Research Grants: Revenue and Expenditure

Total Revenue: $2,520 (in thousands)

A	AIF	$46,000.00
B	CFI	$93,014.61
C	CIFAR	$42,495.02
D	CRC	$100,000.00
E	GDC	$165,000.00
F	iCORE	$1,128,000.00
G	MITACS	$54,000.00
H	NSERC	$683,439.50
I	QuantumWorks	$56,400.00
J	Other	$76,612.32
K	University of Calgary	$75,000.00



Total Expenditures: $2,490 (in thousands)



A	Student Salaries	$259,154.48
B	Studentships & Fellowship/ Scholarships	$377,641.72
	Research Fellows & Associates Salaries	$364,689.84
	Administrative Support Salaries	$87,785.14
	Technical Support Salaries	$87,269.52
	Faculty Salaries	$563,623.91
	Benefits	$131,813.58
	Materials & Supplies	$132,263.32
	Equipment & Freight	$225,049.20
	Travel	$128,298.50
	Visitors	$91,524.55
L	Other	$40,558.60

VII PLANS AND REQUIREMENTS FOR NEXT YEAR

A. Research Objectives

DR. DAVID FEDER

Our group is focused on three particular problems related to the implementation of quantum logic. The first of these is the broad question "What kinds of quantum states are useful in quantum computation?" In the measurement-based model of quantum computation (MBQC), a computation is performed solely by making measurements on some carefully-chosen quantum state. While this state must possess some entanglement to be a useful 'resource,' it is not known how much entanglement is needed or how it should be distributed among the constituents. We will initially consider the set of states that is equivalent to known resource states under local operations, assuming the outcomes are generally known. We then will generalize the results to different kinds of systems. This work is being carried out by PhD student Adam D'Souza.

The second question is "How can one represent algorithms phrased within the quantum circuit model as a quantum walk on a graph?" In a quantum walk (QW), a quantum particle travels through a graph much like a classical random walker, except that it can take multiple paths simultaneously. While numerous quantum algorithms have been developed within the QW framework, a systematic approach for finding new algorithms is not known. Together with PhD student Michael Underwood, we are investigating various mappings between the quantum circuit and QW models of quantum computation.

The third question is "Can indistinguishable particles be used to perform universal quantum logic?" In the usual approach to quantum computation, one envisages a number of independent quantum bits (qubits for short) on which one applies various unitary operations. Each qubit carries independent quantum information. Because all quantum particles are fundamentally indistinguishable (bosons or fermions), however, the usual model requires that each qubit be well-isolated from the next to ensure we know which information resides where. We are exploring the various ways in which the fundamental indistinguishability of particles can be harnessed to perform universal quantum computation.

DR. GILAD GOUR

For every interesting restriction on operations, there is a resulting resource theory. For instance, the restriction of local operations and classical communication (LOCC) in quantum networks leads to the theory of entanglement. Our group's plan for 2010/2011 is to develop new quantitative resource theories that correspond to a variety of natural restrictions that occur in many physical systems of interest. These include super-selection rules (SSR), the absence of a shared reference frame, imperfect apparatus, and restrictions to Gaussian operations in quantum optics. As these limitations occur naturally in quantum networks, it is critical to overcome them in the most efficient way. The mathematical models to be developed will provide novel techniques to distribute resources in quantum networks, provide analytical methods to quantify quantum resources, propose operational interpretations for the different quantifying measures, identify efficient ways to overcome the set of restrictions, and identify and promote the applications of these new resources, especially in fields such as quantum cryptography.

DR. PETER HØYER

The group within the Department of Computer Science will be investigating correlations between spacially separated parties. We will be developing protocols for distilling non-locality and make contributions towards characterizing non-locality. This work will contribute towards understanding the nature of correlations arising through quantum mechanical systems.

Quantum random walks is one of the most promising and successful algorithmic tools we know for achieving efficient quantum computations. Our group will be investigating ways of making random walks more robust against errors and faulty computations. Our work contributes towards making implementations of quantum random walks feasible on real physical systems.

Our group will also be exploring other tools for developing efficient algorithms, including proving statements on the speed-up that is possible by adiabatic computations and seeking a further understanding of how the tensor product nature of quantum mechanical systems can be harnessed to compute boolean functions significantly faster than classical.

DR. ALEX LVOVSKY

- Understand the reasons for the degradation and improve the lifetime of quantum memory for light based on electromagnetically-induced transparency. Develop full quantum theoretical understanding of this memory and reconcile it with the experimental data acquired by continuous-variable quantum process tomography.
- Demonstrate quantum-optical technology at the two-photon level, i.e. preparation and homodyne tomography of arbitrary superpositions of zero-, one, and two-photon Fock states in a single optical mode.
- Demonstrate rudimentary quantum-state engineering with the new quantum light source based on four-wave mixing in hot atomic vapors.
- Commence experiments on trapping atoms and manipulating atomic states with evanescent fields from optical nanofibers.
- Perform quantum process tomography of the photon annihilation operator.

DR. BARRY SANDERS

Machine learning

Machine learning has proven to be quite useful in quantum information processing. We have seen in the past year that machine learning has allowed us to produce the best known feedback-based quantum measurement procedure, and our method should be adaptable beyond the ideal regime to practical settings. The other way that we have used machine learning has been for producing superior coding and decoding to overcome channel errors without increasing the measurement overhead, and we achieved orders of magnitude better performance of the block error rate this way.

Therefore, a key objective in the coming year will be to exploit machine learning to improve quantum measurement and quantum decoding even further and to learn from these efforts. For quantum measurement, we plan to develop new quantum-enhanced measurement strategies for noisy environments. Specifically, the training will take place in simulations of real-world setting to identify the best procedure and characterize its performance.

If this investigation is successful, we are hopeful that we will be able to adapt the learning process to the real world directly without the need for simulation. Ultimately, the goal is to set up an optical source and interferometer with the output directed to photodetectors that are rigged to control the source and interferometer through feedback, and then train this laboratory-based system to find its own best measurement procedure. If we can make this training work in a real-world environment, then we do not have to model noise and loss in nature as the training is done in the real world directly. In this way we have avoid model-dependent procedures.

Quantum decoding

We also plan to build on our quantum decoding work using belief propagation by considering more general channels. One of the big problems in the field is how to perform fault-tolerant quantum error correction for universal circuits highly efficiently. Of course we know that, formally, quantum error correction can be performed efficiently, but current levels of achievable efficiency still place huge burdens on requirements for quantum information processing. Our hope is that belief-propagation methods will find highly efficient coding-decoding strategies that will make error correction practical for hundreds-of-qubits quantum computer, especially those used for quantum simulators.

Quantum reference-frame studies

Quantum information processing demands resources that we do not require or else take for granted in classical information processing. One such resource is quantum reference-frame information. In non-quantum information processing, a zero or one logical state can be encoded, for example, in the voltage of an electronic pulse and be distinguished in any part of the computer or communication network. Quantum encoding may

be built into various degrees of freedom such as the spin of an electron or the polarization of a photon or the magnetic flux of a superconducting junction. For such diverse media, local measurements must be aligned in the sense that both parties have their spin or polarization or magnet reference frames aligned. Such alignment can itself require quantum communication, and the requisite quantum information can degrade during the processing hence need replenishing.

Quantum reference frame studies are at an early stage but are progressing rapidly, yet a major drawback is that the studies focus on pure quantum states. A pure quantum state is ideal in the sense that perfect, complete knowledge is required to specify the state yet such knowledge is inherently unattainable. Absence of knowledge about the preparation of the state requires a mixed-state description. Our goal is to develop a quantum reference-frame theory, including a proper, consistent accounting of resources for mixed states, in order to assess the costs of establishing and maintaining quantum references frames during processing.

Silicon-surface dangling-bond charge qubit

The silicon-surface dangling-bond charge qubit is a promising way of encoding and promising quantum information. Our plan in the coming year is to develop an accurate model for dynamics of these charge qubit systems using a Hubbard model accompanied by realistic noise. We will investigate both circuit and one-way quantum computing in this system and devise ways to measure the bit-flip and phase-flip timescales for decoherence of these charge qubits. These investigations should lead to experimental tests of qubit dynamics and point the way to control and measurement strategies required to exploit fully the capabilities of quantum information processing on the surface of silicon.

Low-loss nonlinear polaritonics

The concept of using negative-index metamaterials as waveguides to produce large cross-phase modulation between two single-photon level light pulses holds enormous promise for all-optical transistors with applications both to photonic communication and to quantum computing. The recent creation of negative-index metamaterials in the visible part of the electromagnetic spectrum suggests this technology could be realized experimentally in the near term. Our goal in the year to come is to develop accurate models of pulse propagation and pulse collision with nonlinear atomic media placed inside negative-index metamaterial wave guides. We will also devise spectroscopic tests of our descriptions about how atoms interact with the nearby negative-index material. Our hope is that this description will lead to commercial all-optical weak-field switches.

Quantum transport in biological systems

Quantum information has proven to be valuable and exciting beyond the aims of information and communication technology. The concepts of quantum information give us new ways to think about processes in nature. Does nature, particularly in complex systems such as living creatures, exploit quantum information processing? Does the process of evolution "select" processes that have quantum algorithmic advantages? Recent experimental results on quantum-coherent transport of excitons in bacteriochlorophyll suggest that quantum walking is occurring in photosynthesis. This coherent process may even have practical implications for solar cells. One objective in the coming year is to collaborate with members of the University of Calgary's Institute for Biocomplexity and Informatics to demonstrate quantum-coherent transport for a reduction-oxidation reaction in a protein complex to see if quantum coherence holds not just for exciton transport for photosynthesis but also for electron transport for reduction-oxidation reactions.

DR. CHRISTOPH SIMON

We have a number of objectives for the coming year.

- On the topic of quantum gates based on photon-photon interactions, we want to complete our study of the limitations on gate performance that arise from the unavoidable relative-position dependence of the underlying interaction. We will build on these results to perform a detailed feasibility study of the implementation of photon-photon gates based on Rydberg states in atomic ensembles. We will also explore the implementation of such gates based on collisional interactions in Bose-Einstein condensates.

- On quantum memories, we will complete our study of the control requirements for highly efficient spin-echo based quantum memories. We also aim to develop a proposal for a new type of solid-state quantum memory based on magnetic switching of the transition dipole moments.
- On the quantum amplification of light, we will study the role of decoherence (photon loss) and coarse-graining (limited detector resolution) in the transition from quantum to classical behaviour.
- On quantum opto-mechanics, we will systematically compare single-photon and continuous-variable schemes for approaching the quantum regime, with the goal of identifying the approach that is most promising experimentally.

DR. WOLFGANG TITTEL

The objectives for the coming year will be of exceeding complexity, i.e. require merging a large variety of sub-systems developed previously.

Quantum cryptography

- We will demonstrate the distribution of secret keys between the UofC and SAIT using our QKD system. The system will, except for the single photon detectors and the polarization controller, be fully integrated, and feature a clock rate of 100 MHz.
- We will develop single photon detectors featuring trigger rates of several hundred MHz. This will eventually allow increasing the clock rate of our QC system, and hence the secret key rate, by two orders of magnitude.

Integration and networks

- We will demonstrate quantum frame-determined optical switching between different receiver nodes. This will pave the road for future work on networks that go beyond pre-established P2P links.
- We will develop theory to find the best path between a sender and a receiver through a quantum network comprising optical switching nodes.

Quantum relays

- We will set up experiments requiring the simultaneous generation of two photon pairs. In a first step, we will study two-photon interference after the two photons have travelled between the UofC and SAIT. This investigation is related with quantum network architecture that goes beyond optical switching nodes, i.e. networks with entangled nodes.

Quantum memory

- We will demonstrate storage of faint laser pulses encoding qubit states, heralded single photons, as well as entangled photons. These highly complex experiments require merging activities as well as people form the quantum relay team and from the memory team.

B. Space

The Institute had 68 members on 31 March 2010. Of these members, there are 7 faculty members and 1 adjunct faculty member, 7 support staff (including technician, part-time IT support staff and administrative support staff), 7 post doctoral fellows/associates, 7 long-term visiting students, and 39 undergraduate and graduate students. Of all students, the division between the Departments of Physics & Astronomy, Computer Science, and Mathematics & Statistics was 34:3:2. The rapid growth of the Institute puts pressure on the availability of space within the University, and particularly within the Faculty of Science.

Floor plans depicting the use of space are provided in Appendix C. Space limitations are particularly evident in the distribution of students and postdoctoral researchers in the Department of Physics & Astronomy.

C. Institute Funding

The University of Calgary provides $75,000 funding p.a., and the cost of operating the institute is $110,999.68 in 2009/2010, and the operating cost is projected to be $111,170 in 2010/2011.

D. Personnel

Institute personnel comprise the Administrator (1), group administrative assistants (3, supported by individual researcher funding), IT support (1, part-time), webmaster (1, part-time).

VIII APPENDICES

A. CHARTER

Charter of the Institute for Quantum Information Science at the University of Calgary

Name

1. The name of the organization shall be the Institute for Quantum Information Science at the University of Calgary (hereinafter referred to as "Institute").

Supervising Officer

2. Under the University's policy on Institutes and Centres (ss. 3.4 & 4.6), each institute reports to an appropriate "supervising officer" within the University's administrative structure. The supervising officer of the Institute shall be the Dean of the Faculty of Science.

Approval and Review Bodies

3. The bodies responsible for approving, reviewing, and renewing the Institute under the policy on Institutes and Centres (s. 3.5) are the Dean of the Faculty of Science and the Research Development and Policy Committee (RDPC).

Term of the Institute

4. Under the limited-term provision of the University's policy on Institutes and Centres (s. 4.4), the Institute is established for a six and half years term ending 30 June 2011**.** The Institute is eligible for renewal (s. 4.4) upon favourable external review (s. 4.3).

Goals

5. The goals of the Institute shall be:
   a) to establish and maintain leading quantum information science in the areas of quantum algorithms and processing, implications of quantum information on information security and communication complexity, development of physical implementations of quantum information tasks and protocols, and critically evaluate proposals and experimental results in the field;

   b) to educate and train persons with expertise at the frontiers of the allied disciplines of quantum information science;

c) to bring together top researchers in the world in order to further the development of the field of quantum information science through a focused, multi-disciplinary effort;

d) to identify promising research areas that will lead to valuable intellectual property and to conduct research in these areas;

e) to collaborate in complementary research activities in the areas of computer science, engineering, mathematics and experimental and theoretical physics and chemistry.

Targets and Measures of Success

6. At the establishment and/or renewal of an institute, the University's policy on Institutes and Centres (ss. 4.1 & 4.3) requires the setting of targets against which to measure success in adding value. These targets have been developed and will be used to measure success in achieving the above goals during the Institute's term. They are outlined in Appendix 1.

Schedule of Review

7. Under the terms of the University's Institutes and Centres Policy (ss. 4.1-4.3) and Procedures (ss. 2.4-2.6), the Institute undertakes to be reviewed upon the following schedule during its term:

a) at the discretion of the Dean of the Faculty of Science, an internal review after two years of the Institute's limited term;

b) as required by the policy on Institutes and Centres, an external review during the final 18 months of the Institute's term.

In addition, the Institute shall submit an annual report on its activities to the Dean of the Faculty of Science.

Institute Board of Directors

8. a) The governing body of the Institute shall be referred to as the "Board of Directors" (hereinafter "Board").

b) Membership of the Board shall comprise:
   i. The Institute's "supervising officer" (or designate), who shall Chair the Board and appoint a Vice Chair from among other board members;
   ii. At least 4 "members at large," drawn from or nominated by
      - companies whose primary operations are synergistic with quantum information science;
      - agencies that provide funding for quantum information science research in Alberta; and
      - leading members of the quantum information science academic community.

   At least one (1) "member at large" shall be appointed from each of these three categories.

c) The President of the University of Calgary shall appoint "members at large" on the advice of the supervising officer. Terms of appointment, commencing on April 1, shall normally be for three years. This length of appointment may be varied to ensure an appropriate staggering of terms. Members of the Board shall be eligible for re-appointment for consecutive terms of office.

d) The Board shall be responsible for the overall success and governance of the Institute. More particularly, its responsibilities include:
   i. approving and/or amending this Charter under the provisions of clause 10 below;
   ii. ensuring that relevant University policies are respected (see section 9 below);
   iii. appointing a Director for the Institute;
   iv. approving the Institute's budget and strategic plans;
   v. determining membership categories and requirements for the Institute;
   vi. determining the procedures and requirements of general meetings of institute members (with at least one such meeting required annually);
   vii. helping to create opportunities for the Institute;
   viii. facilitating the periodic reviews and external assessments of the Institute, as required by the University's policy on Institutes and Centres (s. 4.3).

e) The Board shall appoint a Secretary of the Board for a three-year term. The Board can revoke such appointment at any time. The Secretary is not a Board Member and is not eligible to vote.

f) The Board shall meet not less than once in each calendar year, prior to the annual general meeting of Institute members. Special Meetings of the Board shall be convened by the Chair of the Board or upon the written request of at least two (2) members of the Board addressed to the Chair.

i. At least thirty days notice of any meeting shall be given in writing to each member of the Board. Such notice shall specify the time, place and agenda of the meeting;

ii. At any meeting of the Board 50 percent of members, present physically or via teleconference, shall constitute a quorum.

g) The cost for Board members of attending Board meetings (annual and special) will be incurred by the Institute.

Director

9. a) The Director reports to the Board and to the University through the Dean of the Faculty of Science (who, directly or through a designate, chairs the Board).

b) The Director exercises a general superintendence over the operational affairs of the Institute in accordance with the goals of the Institute, and within Board-approved budgets and strategic plans.

c) The duties of the Director shall include, but not be limited to, the following:

i. preparing an annual budget and strategic plan for consideration and approval by the Board;

ii. preparing periodic financial updates for consideration by the Board;

iii. ensuring that all Institute policies and procedures adopted by the Board are made widely known among Institute members and stakeholders, including the broader University of Calgary community;

iv. preparing an annual report on the Institute's affairs, which shall include reporting on measures of success;

v. making any additional submissions or reports, as appropriate or requested, to the Board or the University of Calgary on any matter affecting the Institute;
vi. facilitating the periodic reviews and external assessments of the Institute required by the University's policy on Institutes and Centres (s. 4.3).

Policies and Procedures

10. The Institute will operate in accordance with all applicable University of Calgary policies and procedures.

Amendments

11. Amendments to this Charter shall require approval by the supervising officer and two-thirds of the Board. (The supervising officer may refer proposed amendments to RDPC for its advice.)

Appendix 1

Targets and Measures of Success

Measures of Success:

a) Certified national testbed for quantum cryptography
b) Expertise and productive research
c) Demonstrate quantum memory for light
d) Demonstrate quantum optical state engineering at the multiphoton level
e) Establishment of fundamental relations among measures of quantum complexity
f) Theoretical power and limits of quantum models and protocals
g) Demonstrate few-qubit quantum fingerprinting
h) Efficient numerical simulation routines for quantum communication protocols accounting for realistic imperfections
i) Groundwork for applied research in QIS with expectation of valuable intellectual property
j) Self-funding QIS educational arm based on sophisticated visualization technology in collaboration with Banff New Media Institute
k) IQIS is a demonstrable QIS destination of choice for top students, postdocs, visitors, and prospective faculty

Specific Targets to Achieve by 2010:

Highly Qualified Personnel

- 30 graduate students with median entrance GPA > 3.75 or equivalent
- 2 external awards for students annually
- 8 postdocs including 4 with external fellowships
- 4 annual undergraduate student projects
- 5 summer students including at least 3 NSERC summer scholars
- 7 tenured or tenure-track faculty in QIS including 4 externally funded chairs (*i*CORE, IRC, CRC, ...)

Education and Training

- 3 graduate courses offered in QIS

- Annually: 4 students/postdocs visiting collaborating institute for at least 4 weeks
- Establishment of QViz as the premier source of sophisticated visualization presentations of QIS

Research Inputs
- At least $1,200,000 external funding for QIS research, stipends, scholarships, and fellowships per annum
- 8 distinguished visitors per annum
- 5 visitors at PhD level or higher per annum who stay at least 4 weeks

Research Outputs
- 30 papers in international refereed journals or refereed conference proceedings per annum including
- 8 in Physical Review Letters, or FOCS/STOC/STACS/ICALP/Complexity
- 1 in Science or Nature every second year commencing in the third year after the establishment of the Institute
- 30 invitations to give talks per annum including 3 keynote/plenary talks
- 15 student oral or poster presentations per annum at QIS conferences

Collaborations
- Demonstrable collaboration with at least 5 leading QIS groups
- Student exchanges with at least 2 leading QIS groups
- At least one corporate partnership with >$100k annual cash support
- Major experimental research project with leading international partner

Service
- Memberships of 8 conference/workshop program committees annually
- Chair or Co-Chair at least one conference biennially
- At least 2 editorial board members of QIS-related journals

B. Performance Indicators

achieved; not yet achieved

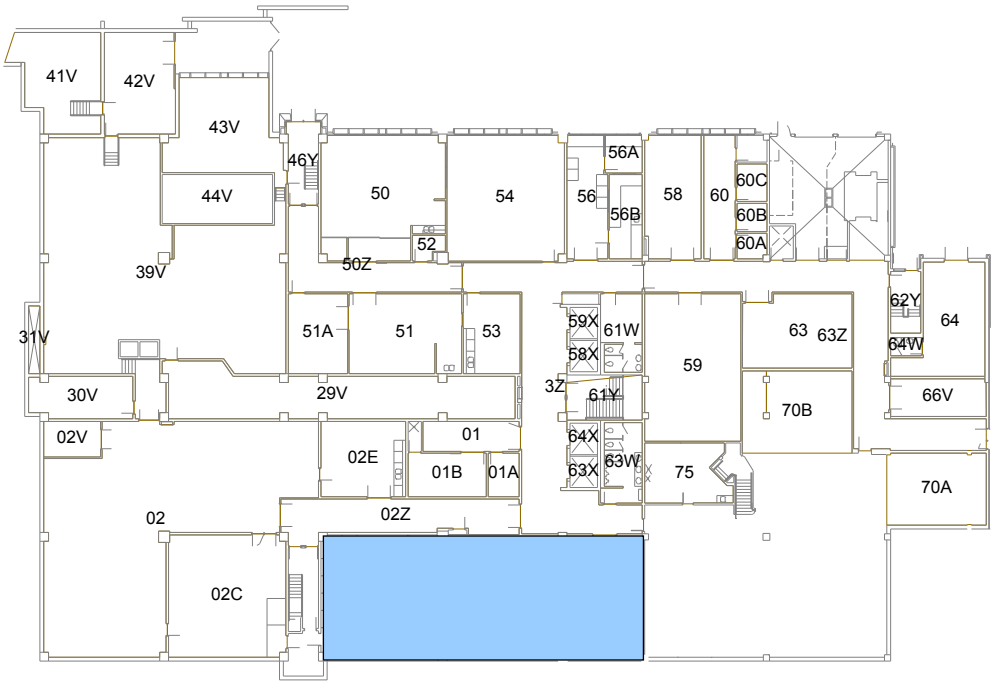
Key result areas /performance indicators	*Target (by 2010)*	*Achievements (2008/09)*
	Highly Qualified Personnel	
Number of students	30 graduate students	34
Median GPA	30 graduate students with median entrance GPA >3.75 or equivalent	
	- MSc	3.52
	- PhD	3.43
External Awards	2 external awards for students annually	11
Number of postdoctoral associates	8 postdoctoral associates	7
External Fellowships	8 postdoctoral associates including 4 with external fellowships	1
Undergraduate student projects	4 annual undergraduate student projects	7
Number of summer students	5 summer students including at least 3 NSERC summer scholars	1 – others 4 – NSERC
Number of tenured or tenure-track faculty in QIS	7 tenure-track faculty	7
External funding of faculty	4 externally funded chairs (*i* CORE, IRC, CRC)	3
	Training and Education	
Number of graduate courses	3 graduate courses offered in QIS	6
Students/postdocs visiting collaborating institutes	4 students/postdocs annually visiting collaborating institutes for at least 4 weeks	2
	Research Inputs	
Distinguished visitors per annum	8 distinguished visitors per annum	6
Number of visitors	5 visitors at PhD level or higher per annum who stay at least 4 weeks	8

Key result areas /performance indicators	*Target (by 2010)*	*Achievements (2008/09)*
Research Inputs (cont'd)		
Number of publications	30 papers in international refereed journals or refereed conference proceedings per annum including	43
	* 8 in Physical Review Letters, or FOCS/STOC/ STACS/ICALP/Complexity	4
	* 1 in Science or Nature every second year commencing in the 3rd year after the establishment of the Institute	2
Invitations to address conferences	30 invitations to give talks per annum including 3 keynote/plenary talks	40 (3 - keynote/ plenary talk)
Number of student presentations	15 student oral or poster presentations per annum at QIS conferences	36
Collaborations		
Number of collaborations	Demonstrated collaboration with at least 5 leading QIS groups	7
Number of student exchanges	Student exchanges with at least 2 leading QIS groups	1
Corporate partnership	At least one corporate partnership with >$100k annual cash support	1 - GDC
Major experimental research project	Major experimental research project with leading international partner	0
Citizenship		
Program committee membership	Membership of 8 conference/workshop program committees annually	14
Chair or Co-Chair	Chair or Co-Chair at least one conference biennially	1
Editorial board membership	At least 2 editorial board membership of QIS-related journals	4

C. Floor Plans for Existing Use of Space

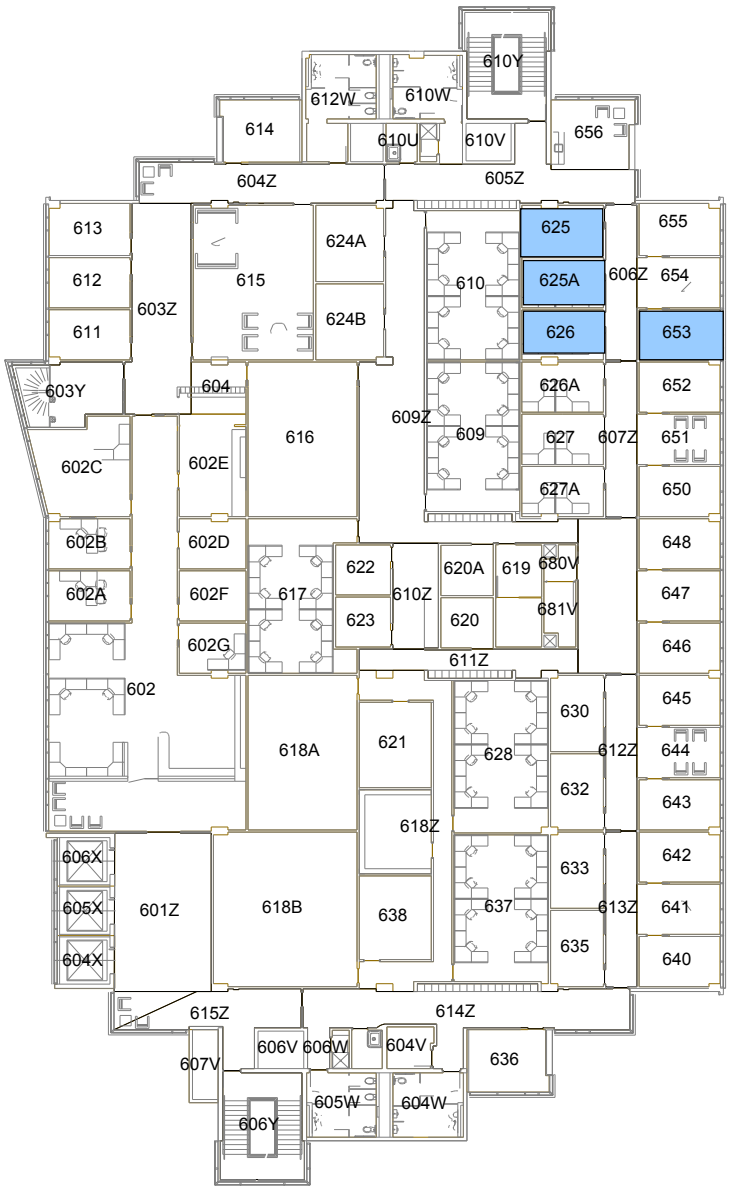
Earth Science Basement

IQIS



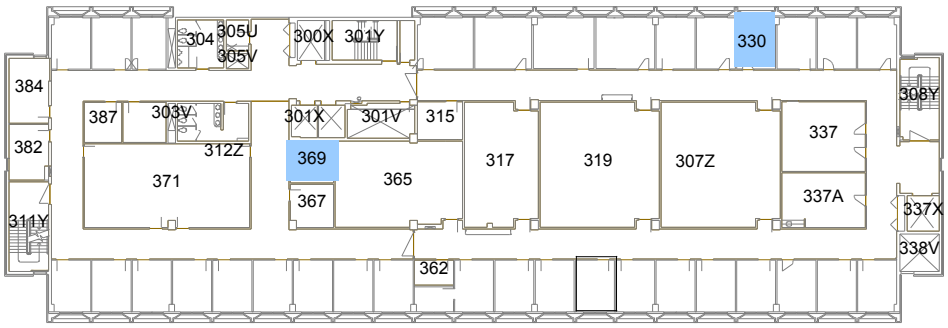
ICT Sixth Floor

IQIS



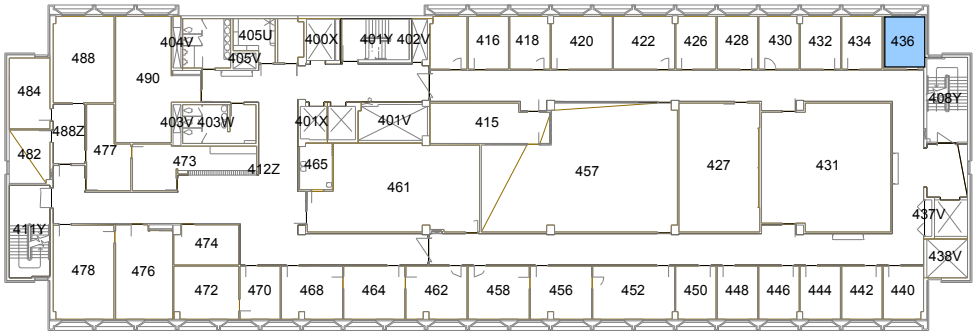
Mathematics Third Floor

IQIS



Mathematics Fourth Floor

IQIS



Science B Basement

IQIS

Science B Main Floor

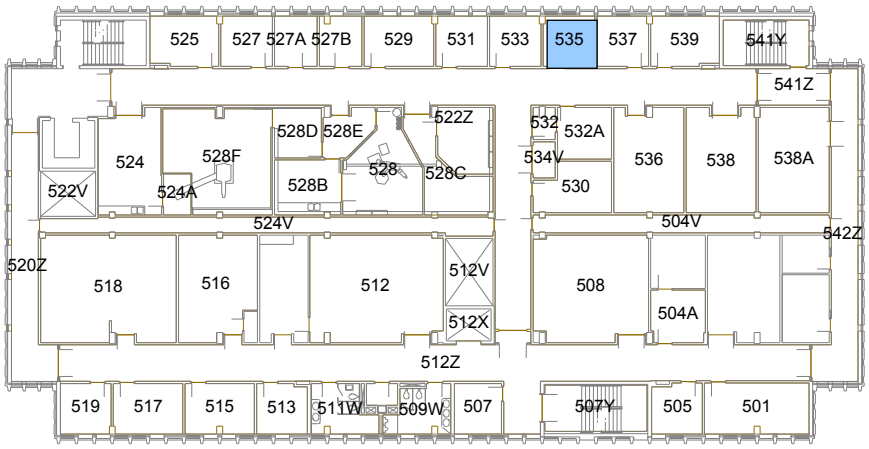
IQIS

Science B Third Floor

IQIS

Science B Fifth Floor

IQIS



IQIS adds value to the University of Calgary in the following ways:

- **Fosters** a multidisciplinary research team through financial, administrative, and computer support
- **Builds** a quantum information research community by providing visitor, seminar, and colloquium programs
- **Assists** new faculty members with a rapid transition to becoming productive researchers with a strong research group and necessary equipment
- **Publishes** reports and web pages that ensure recognition of the Institute and its researchers as leaders in quantum information
- **Supports** recruiting efforts to bring the best faculty members, postdoctoral researchers, and graduate students to the University
- **Sponsors** and provides logistical support for leading international conferences to be held in or near Calgary
- **Partners** with other quantum information institutes within national and international research and training networks
- **Enhances** the University's reputation by conducting and disseminating outstanding research results
- **Provides** benefit to the community by generating new knowledge in a strategic area

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