Quantum Science and Technology

PERSPECTIVE

Quantum Canada

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Abstract

Canada ranks among the world's leading nations in quantum research, building on investments of more than $1 billion in the past decade alone. Canada's amassed research expertise, growing private-sector impact, and government commitments to innovation and competitiveness, place the country in a strong position, as scientific advances drive quantum technology development. Here, we summarize the steps Canada has taken to build quantum research excellence and to support a growing quantum industrial base. We also discuss Canadian quantum community efforts to solidify and build the nation's leadership, as the technology revolution unfolds.

Canada: well-positioned for continued quantum leadership

Over the past decade, Canada has invested more than $1 billion in quantum science and has established its position among the world's leading nations in quantum R&D. In a recent evaluation of worldwide quantum research efforts published in the *Economist* [1], McKinsey and Co. ranked Canada 5th globally in total annual expenditures on quantum science ($100 M Euros) and 1st among G7 nations in per-capita spending on quantum research. These significant investments have helped create a critical mass of world-leading university research talent across the country, as well as earning Canada a strong global reputation for its quantum science excellence and its many transformative research findings. A 2016 assessment of innovation across G20 nations placed Canada 5th worldwide for patent filings in the area of quantum computing and telecommunication [2].

As quantum investigations move into the innovation phase, Canada's amassed expertise provides the country with a major opportunity to translate strong science into technology leadership. Canadian and international research over the past several decades has expanded understanding of quantum mechanics, giving researchers the ability to harness quantum effects for technology development. In the past several years, questions around quantum technologies have moved beyond 'if' and are now focused on 'when'—and in some cases, 'where'.

As the start of the quantum technology revolution moves ever closer, Canada is in a position of strength, with world-class science, growing private-sector engagement, and a public sector with a stated commitment to embracing innovative technologies in order to maintain global competitiveness.

History of Canadian quantum research advances

Canadian scientists have been pushing the boundaries of quantum research for many decades. In 1984, Gilles Brassard at the Université de Montréal and Charles Bennett at IBM Research introduced the first scheme to encrypt information using the properties of quantum mechanics. Brassard is rightly known as Canada's 'father of quantum information' because of this pioneering work. Since then, Canadian scientists and research institutions have further advanced the science through discoveries in areas that include the following: photonic quantum computing, measurement-based quantum computing, mathematical aspects of quantum information processing, solid-state quantum computing, adiabatic quantum computing, quantum metrology, quantum communication, quantum networks, quantum cryptography and related software, as well as quantum materials

and quantum-material based devices as a foundational enabling technology. These advancements have been accompanied by progress in development and refinement of several physical platforms for quantum technologies, including photon-matter interfaces, spin-based qubits, and superconducting qubits.

The nation's private sector is also driving progress. One of Canada's business leaders, Mike Lazaridis, founder of Research in Motion—which became Blackberry Limited—has been a champion of quantum as the next big technology revolution. Lazaridis and his business partner Doug Fregin donated $150-million to support the 2001 creation and ongoing operations of the Institute of Quantum Computing (IQC) in Waterloo, Ontario. A recent investment includes the establishment of the Quantum Valley Ideas Laboratory: an independent, not-for-profit quantum technology development laboratory.

In addition, Canada is home to many quantum start-ups, as well as one of the most internationally recognized companies in quantum computing, D-Wave Systems in Vancouver, British Columbia.

Supporting the best quantum science

Canada's investments in quantum research have been largely guided by competitive processes and 'merit-based' selection of funding recipients. The country's research-funding framework has supported the highest quality of scientific discovery and given researchers considerable freedom to advance knowledge in areas where technology applications may not yet be defined. Canada's support of the best science has yielded advances of global importance in the quantum field, and has produced a strong national 'ecosystem' of research expertise that positions Canada to continue its leadership in the coming era of quantum technologies.

The contributions of several Canadian granting organizations have laid the foundations for Canada's quantum research excellence.

NSERC

The investment programs of the Natural Sciences and Engineering Research Council of Canada (NSERC) support university-based discovery research and innovation and university students in advanced studies, as well as networks and collaborations among academic institutions and with Canadian companies. NSERC awarded $267.2 million for quantum research between 2006 and 2015, and awards valued at $43 million in 2015 alone.

CFI

The mandate of the Canada Foundation for Innovation (CFI) is to significantly build Canada's capacity to undertake world-class research and technology development. The CFI, along with provincial partners, has invested more than $100 million to build quantum-related research infrastructure across the country, which has enhanced Canada's ability to attract and retain top researchers in the quantum field [3].

CIFAR

The Canadian Institute for Advanced Research (CIFAR) is a private, not-for-profit institution that invests $25 million a year to support outstanding researchers in 14 different interdisciplinary conference programs across the country, including quantum research. CIFAR provided key early support of quantum research initiatives, creating its Quantum Materials program in 1987 and its Quantum Information Science program in 2002.

One of the distinguishing features of CIFAR is the global reach of its programs, with nearly 50% of members based outside Canada.

CFREF

The quality and potential of the country's quantum research have been significantly elevated by the Canada First Research Excellence Fund (CFREF), a tri-agency initiative of NSERC, the Social Sciences and Humanities Research Council, and the Canadian Institutes of Health Research. The fund supports the highest international standards of research excellence in areas where Canadian science is already strong and presents opportunities for building world-leading capabilities and long-term economic advantages for Canada.

This program has provided major funding for three quantum research programs in Canada:

- *Institut quantique (IQ): Université de Sherbrooke*
  The Université de Sherbrooke was awarded a CFREF grant of $33.5 million in 2015 to build on its expertise in quantum information and quantum materials. The funding supports research focused on the interface of these two fields and quantum engineering, an intersection offering immense potential for discovery and innovation—from the new materials offering enhanced information-processing capabilities and techniques, to new methods for studying and probing quantum materials. The initiative seeks to develop a synergy between these fields, while taking advantage of the micro-nanofabrication and quantum engineering expertise

at the Université de Sherbrooke's Interdisciplinary Institute for Technological Innovation (3IT) and MiQro Innovation Collaborative Centre (C2MI).

- *Stewart Blusson Quantum Matter Institute (QMI): University of British Columbia*
  The QMI was awarded a $66.5-million CFREF investment in 2015 to support the program Quantum Materials and Future Technologies. The funds are being used to discover and develop new quantum materials by design, and exploit them in the fabrication of novel quantum devices that could lead to pioneering technological applications in computing, electronics, medicine, and sustainable energy. This research initiative builds on the strengths of Canada's top physics institutes, including TRIUMF at UBC, the Canadian Light Source at USask, and the Canadian Centre for Electron Microscopy at McMaster. It also aims to build upon and further expand major international partnerships such as, in particular, the prestigious Max Planck-UBC-UTokyo Centre for Quantum Materials.
- *Transformative Quantum Technologies (TQT): University of Waterloo*

In 2016, the University of Waterloo received a CFREF award of more than $76 million, with additional partner contributions of $68 million, for an overall $144-million TQT initiative that brings together physics, chemistry, materials science, computer science and engineering to advance the development of deployable quantum devices. Technologies under development include low-noise quantum processors; quantum sensors with applications in navigation, materials, biochemistry, medicine and other fields; and systems for controlling long-distance quantum entanglement. In the Waterloo Region, key research institutes have received significant investments from government, as well as industry and philanthropic organizations. Over the past 20 years, these investments have included: $568 million in the Institute for Quantum Computing, $205 million in Quantum Valley Investments and $591 million in the Perimeter Institute.

The establishment of the three CFREF-funded quantum programs and other funding investments have laid a foundation for Canada's continued science excellence in the field, while also creating opportunities for applied-research breakthroughs that are opening the door for commercial applications in a range of viable systems and platforms.

Canada has additional strengths and initiatives to support innovation as the quantum field develops from laboratory-based science to the structures of an industrial ecosystem.

International partnerships

It is critical to connect the best Canadian scientists with the best scientists around the world to generate transformative new knowledge. Through the work of CIFAR's quantum programs and many high-profile international partnerships across the country [for example, QMI at UBC with the Max Planck Society of Germany and the University of Tokyo (MP-UBC-UTokyo Centre for Quantum Materials); and IQ with UMI-LN2 (France + EU Flagship)], Canadian researchers have been working with international colleagues to push the frontiers of quantum science. This collaborative international research has supported Canada's development as one of the world's leading quantum nations and these valuable partnerships are needed to ensure ongoing leadership.

Canada's research excellence from coast to coast

Provincial research networks: Quantum Alberta in Alberta; Regroupement Québécois sur les Matériaux de Pointe (RQMP); Institut Transdisciplinaire d'Information Quantique (INTRIQ) in Quebec

Research institutes: Stewart Blusson Quantum Matter Institute (QMI) at University of British Columbia; Max Planck-UBC-UTokyo Centre for Quantum Materials; Institute for quantum science and technology (IQST) at University of Calgary; Institute for Quantum Computing (IQC) at University of Waterloo; Centre for quantum information and quantum control (CQIQC) at University of Toronto; Institut quantique at Université de Sherbrooke; Brockhouse Institute for Materials Research; Perimeter Institute for Theoretical Physics

Research groups: University of Victoria, Simon Fraser University, University of Lethbridge, University of Alberta, University of Saskatchewan, University of Manitoba, McMaster University, Queen's University, University of Ottawa, McGill University, Université de Montréal, Laval University, Dalhousie University

Federal government research labs: National Research Council; TRIUMF; Canadian Light Source

Quantum R&D in government institutions

The National Research Council (NRC) is the Government of Canada's largest research organization, with a mandate to support industrial innovation, and to advance knowledge and technology development in areas that will help Canada address current and future economic, social and environmental challenges.

In recognition of the strategic importance of quantum innovation, in 2014, the NRC created a $50- million (over 7 years) Quantum Photonics Sensing and Security (QPSS) R&D program. The program is focused on advancing scientific knowledge and the development of quantum applications that include prototype technologies in cyber-security and advanced security, and in environmental and health sensors.

Other government agencies are exploring early adoption of quantum technologies with research that could be translated to private-sector, commercial applications. The Communications Security Establishment (CSE) is engaged in quantum cryptography investigations, and Defence Research and Development Canada (DRDC) is undertaking R&D in quantum sensing, quantum-based position-navigation timing, and other potential military applications.

The NRC, CSE and DRDC have jointly founded the Quantum Security Technology Access Centre (QSTAC) to accelerate development of quantum-enhanced cyber security solutions to protect critical IT infrastructure. QSTAC has undertaken numerous joint research projects with leading Canadian researchers from the University of Toronto, University of Calgary, University of Ottawa, the Institute of Quantum Computing at the University of Waterloo, and the Institut quantique at the Université de Sherbrooke.

The federal government also made a commitment in the 2018 budget to provide the NRC with $150 million over five years, with $30 million per year ongoing, 'to catalyze transformative, high-risk, high-reward research with the potential for game-changing scientific discoveries and technological breakthroughs [4].' The new investment will augment NRC programs, such as QPSS, to work with innovators from post-secondary institutions and businesses on multi-party research and development programs.

Quantum Encryption and Science Satellite (QEYSSat) mission

In 2017, the Canadian government provided the Canadian Space Agency (CSA) with $80.9 million in multi-year funding for emerging technology research, including in quantum technologies. The CSA is undertaking a major scientific mission to demonstrate quantum key distribution (QKD) in space, with the aim of advancing encryption methods to protect the security and privacy of digital information. Current QKD technology relies on ground fibre optic cables and is currently limited to a distance of a few hundred kilometres. The mission would seek to demonstrate QKD between a satellite and a grounded network as a way to overcome the distance limits [5].

The industrial base

Among the goals of the Canadian government's Innovation Agenda is to 'identify ways for Canada to harness emerging technologies that would create jobs and industries that never existed before, while invigorating established industries.' Canada has a strong base of industries that stand to be invigorated by quantum technology advances, and whose capacities in design, manufacturing and distribution could support development of quantum systems and devices.

Such anchor industries include Canada's photonics sector, in which approximately 400 photonics companies employ more than 25 000 people and collectively generate close to $4.6 billion in revenue each year [6].

Established firms are exploring the incredible sensitivity of quantum sensors for their application areas. For example, Imperial Oil is using quantum sensors for oil extraction, with the goal of developing more environmentally friendly processing for the Alberta oil sands. Schlumberger has also invested in quantum gravity sensors that have better sensitivity for oil exploration.

Across Canada, strong university centres and great student interest have led to many quantum start-ups, and translation is underway to grow these start-ups into small and medium-size enterprises. Opportunities exist to develop world-leading multinational enterprises. Support structures and local quantum communities include the Quantum Valley in Waterloo and Toronto's Creative Destruction Lab.

Canada boasts a number of fast-growing leaders in quantum enterprise, including D-Wave Systems (developing quantum annealers) and ISARA (developing quantum-safe security solutions). Other disruptive quantum-technology companies are emerging in many regions of Canada; among them are 1QBit, Anyon Systems Inc., evolutionQ, Xanadu, Quantum Benchmark, Quantum Silicon, and RANOVUS.

Looking forward: the tipping point

Quantum science is at the 'tipping point'—the pivotal point at which the building blocks of quantum-enabled technologies have been demonstrated in the laboratory and are emerging into the 'real world' of commercial applications. From absolutely secure communications to enhanced medical and environmental sensors, there is

increasing evidence of the transformative impact that cutting-edge quantum science will have on a range of different technology areas.

The institutions and researchers in Canada's quantum field are amplifying their efforts to coordinate future scientific research and innovation efforts to prepare the nation for the coming quantum technology revolution. In April 2017, NRC, NSERC and CIFAR co-hosted a Quantum Canada symposium and workshop that brought together leading Canadian and international quantum stakeholders from research centres, companies and government. Discussions built upon an earlier survey of members of the quantum community in Canada, and focused on potential strategies to maintain and expand Canada science excellence in quantum, while also strengthening links between researchers and industrial players and broadening opportunities for converting the science into technology impact for Canada.

A number of initiatives flowed from these strategic explorations. Participants had agreed on the importance of connecting top researchers with industry stakeholders to share ideas about how emerging quantum applications might address various industrial sectors' challenges and aspirations. Sector-specific workshops held to date include defence, and mineral exploration and extraction, with future sessions expected in cyber security and health technologies.

After the symposium and workshop, the NRC commissioned a third-party research project that included influencer interviews and econometric analysis to assess the potential economic impact of quantum technologies in Canada over the next 25 years [7].

The third-party study noted that quantum technology is projected to have a massive impact in the next 5–25 years: first through innovations in sensing and imaging, followed by advances in communications, and then in quantum computing, the application area with the longest development cycle. This assessment concurs with other global studies, while considering domestic industries, for example, Canada's vibrant photonics industry.

The study predicted that the impacts of quantum technologies will be felt across several sectors important to the Canadian economy, including communications, mining, agriculture, finance, defence and security, health, energy, and big data. Traditionally, Canada has been able to capture 4% of the global market share in a technology trade, and based on the results of the third-party economic study, Canada is anticipated to capture a larger share in the next decade. In some scenarios, the study anticipated that Canada could reach up to 8% of the world's market share in this field, given its research and industrial capacities.

Countries around the world are launching their national quantum strategies, looking to channel the potential of quantum science into technology and innovation. This presents strong prospects for Canadian quantum researchers to collaborate with colleagues involved with other national quantum initiatives, through opportunities that could include faculty and student exchanges, and joint large-scale projects.

Today's quantum research ecosystem in Canada was built through a competitive system that rewards and nurtures high-calibre science. The Canadian quantum community recognizes that its current position presents an opportunity, but it cannot stand still in the quickly evolving and competitive global R&D system. The country needs to maintain and expand its quantum science strengths, while also driving development of strategic technologies and industry transformations.

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