



Innovate UK
Global Expert Mission

Quantum Technologies in Canada 2018

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Welcome

Innovate UK's global missions programme is one of its most important tools to support the UK's Industrial Strategy's ambition for the UK to be the international partner of choice for science and innovation. Global collaborations are crucial in meeting the Industrial Strategy's Grand Challenges and will be further supported by the launch of a new International Research and Innovation Strategy.

Innovate UK's Global Expert Missions, led by Innovate UK's Knowledge Transfer Network, play an important role in building strategic partnerships, providing deep insight into the opportunities for UK innovation and shaping future programmes.

In March 2018, twelve of the leading experts in the UK quantum technology industry flew to Waterloo in Canada as part of Innovate UK's Quantum Technologies Global Expert Mission. They were invited to attend by the National Research Council Canada and the Knowledge Transfer Network, on behalf of Innovate UK with the support of the Engineering and Physical Sciences Research Council (EPSRC)¹.

Led by Sir Peter Knight², the UK representatives of industry, academia and government, travelled to Ottawa, Waterloo and Vancouver, where they visited the National Research Council, the University of Ottawa, the Institute for Quantum Computing in Waterloo, the Perimeter Institute, Quantum Valley Investments, Velocity Garage, D-Wave Systems, Simon Fraser University and the University of British Columbia; and had meetings with representatives from the universities of Sherbrook and Calgary, Creative Destruction Lab, the Government of British Columbia, NSERC, CFI, Universities Canada and several quantum technology companies.

In this publication, we share the information and insights gathered during their time in Canada.

¹ <https://epsrc.ukri.org>

² <https://royalsociety.org/people/peter-knight-11760>

1. The Quantum Landscape

With underpinning experience in semiconductors, photonics and IT, Canada is positioning itself to be a global leader in quantum science and technology and its commercialisation and industrialisation. There is a feeling that this is a critical area for the future security, wellbeing and wealth of their nation – and one in which they can excel. The quantum technologies vision goes all the way to the Prime Minister.

On 18 September 2017, the Prime Ministers of Canada and the UK signed a Memorandum of Understanding (MoU)^{3,4}, that explicitly identifies quantum technology as an area for cooperation, with the potential to grow businesses and create jobs. The Canadian Discovery Science Budget 2018⁵ emphasised international collaboration, and a national effort is to be coordinated under the Quantum Canada⁶ banner. The aim of the expert mission was to find out how both countries can make the most of these auspicious developments.

Canada's thriving quantum technology system involves academia, start-ups, venture capital investors, high-class facilities and government buy-in. Over the past decade, Canada has invested more than C\$1 billion in quantum R&D, and about 350 researchers are working on quantum technology.

There are close scientific parallels between the UK and Canadian quantum communities. For example, photonics is a powerful industry in both countries, and underpins much of the quantum research activity. Quantum photonics work in Ottawa and in Waterloo has very close parallels with UK research in Oxford, Bristol, Bath, Cambridge and Strathclyde.

1.1 Recent Developments

1.1.1 Quantum Canada

Quantum Canada is a nascent initiative by the NRC, NSERC and CIFAR to coordinate national quantum research and innovation. The aim is to “deliver a cohesive vision for Canada's national interests in quantum, and to ensure that Canada maintains and expands its present-day advantage in this emerging sector”⁷. The strategy used to achieve this goal is still under discussion, due to be published in January 2019.

Preliminary ideas from a workshop in April 2017 are laid out in the report *Seizing Canada's Quantum Opportunity*⁸.

Quantum Canada will be able to build on existing collaborative arrangements, such as the Quantum Security Technology Access Centre (QSTAC)⁹, a joint programme between NRC and the Communications Security Establishment to give guidance on how quantum technology will affect security, defence, computing and communications. QSTAC supports collaborations between the universities of Ottawa, Toronto, Waterloo, Sherbrooke and Calgary.

1.1.2 Budget Boost

The 2018 budget provided large funding increases for scientific research, including an extra C\$355 million (£210 million) for NSERC over the next five years.

A new tri-council fund (worth C\$275 million over five years, shared between NSERC, the Social Sciences and Humanities Research Council and the Canadian Institutes of Health Research) is to support research that is “international, interdisciplinary, fast-breaking and higher-risk”¹⁰. Collaboration on quantum technology would fit all those criteria.

1.1.3 Superclusters

The 2017 budget provided C\$950 million to fund five innovation superclusters. These are industry-led consortia that are tasked with building world-leading innovation hotbeds. With matched industry funding, they will aim to attract talent, increase business spend on R&D, generate new companies, commercialise new products, connect to global supply chains and “strengthen collaborations between private, academic and public-sector organizations pursuing private-sector led innovation”¹¹.

³ <https://pm.gc.ca/eng/news/2017/09/18/prime-minister-canada-announces-closer-collaboration-united-kingdom>

⁴ www.gov.uk/government/news/uk-and-canada-pledge-to-work-together-to-develop-emerging-technologies

⁵ www.budget.gc.ca/2018/docs/plan/chap-02-en.html

⁶ www.nrc-cnrc.gc.ca/eng/solutions/collaborative/quantum/quantum_canada.html

⁷ www.nrc-cnrc.gc.ca/eng/solutions/collaborative/quantum/quantum_canada.html

⁸ www.nrc-cnrc.gc.ca/obj/doc/solutions-solutions/collaborative-collaboration/quantum_canada-quantique_canada/2017_Symposium_Workshop_Report.pdf

⁹ www.nrc-cnrc.gc.ca/eng/about/planning_reporting/evaluation/2017_2018/sdt_report.html

¹⁰ www.budget.gc.ca/2018/docs/plan/chap-02-en.html#Investing-in-Canadian-Scientists-and-Researchers

“What is a supercluster? It is a made-in-Canada Silicon Valley that will create tens of thousands of jobs.”

Navdeep Bains, Minister of Innovation, Science and Economic Development

Two of the winning bids are relevant to quantum technology:

- AI-Powered Supply Chains Supercluster (SCALE.AI)¹², based in Quebec and Ontario with C\$200 million federal funding. The AI supercluster is focused on applying AI to supply chains, for example through demand forecasting, product customisation, pricing and flow optimisation. “SCALE. AI will bring the retail, manufacturing, transportation, infrastructure, and information and communications technology sectors together to build intelligent supply chains through artificial intelligence and robotics.”
- Digital Technology Supercluster¹³, based in British Columbia with C\$200 million federal funding. Encompassing data collection, analysis and visualisation, the supercluster already includes more than two hundred companies. Founding members include Microsoft and the University of British Columbia. Within 10 years, they anticipate investing more than C\$1.4 billion in more than 100 collaborative projects involving more than 1,000 organisations, generating an estimated C\$15 billion in incremental GDP and 50,000 new jobs. “Working together across sectors, our supercluster will identify and advance projects that are guided by defined industry needs. With an initial focus on health, natural resources and industrial projects, we will innovate solutions using data analytics, quantum computing, and virtual, mixed and augmented reality.”

1.2 Quantum Places

The country is strongly regionalised, with science, industry and society all focused on its main cities, and quantum technology follows the same pattern. There are very strong local concentrations of activity such as Waterloo’s Quantum Valley. Compared with the UK, there is less cross-country collaboration – in part because of the great physical distances – although that may soon grow through the Quantum Canada initiative (see ppXX).

1.2.1 Quantum Valley, Waterloo

In Waterloo, several institutions form a network that may be the stand-out example of a big vision for quantum research and technology. These institutions are very well funded, largely thanks to donations from Michael Lazaridis (the founder of Blackberry) providing large, well-designed and equipped purpose-built facilities, and supporting and attracting global talent.

- The Institute for Quantum Computing¹⁴ (IQC) is a cross-disciplinary institute within the University of Waterloo. Its aim is to explore quantum information in a broad sense, encompassing computing, communications and sensors. With almost 300 researchers in physics, mathematics, computer science, engineering and materials, this is on a much larger scale than any single research centre in the UK. Mission participants were impressed by the physical layout and space available at two locations: the Quantum Nano Centre (which includes the Quantum NanoFab fabrication facility); and the Research Advancement Centre. IQC supports collaboration between academic and industry teams, the top floor occupied by companies, where IP is protected while lower floors house academic research facilities where conversations and engagements are open and unprotected. Its growth lab is a facility to grow microfabricated layers of a multitude of materials in four connected chambers, allowing processes to be carried out very quickly one after the other (minutes, instead of days to months in the case of external facilities). The University of Waterloo promotes spin-outs with the Transformative Quantum Technology programme, which funds research projects that focus on applications.
- The Perimeter institute¹⁵ is aiming to be the world’s leading centre for theoretical physics, focusing on the fundamentals of space, time and quantum mechanics. It is not directly plugged into quantum technology, but it helps to raise the profile of quantum science in Waterloo.
- Quantum Valley Ideas¹⁶ Laboratories works with academia and industry to help commercialise research.
- Quantum Valley Investments¹⁷ funds and supports commercial quantum tech companies.

¹¹ www.canada.ca/en/innovation-science-economic-development/programs/small-business-financing-growth/innovation-superclusters.html

¹² <https://aisupplychain.ca>

¹³ www.digitalsupercluster.ca

¹⁴ <https://uwaterloo.ca/institute-for-quantum-computing>

¹⁵ www.perimeterinstitute.ca

¹⁶ <http://tqt.uwaterloo.ca/quantum-valley>

¹⁷ <http://quantumvalleyinvestments.com>

1.2.2 Sherbrooke

The Institut Quantique¹⁸ was founded in 2015, with the help of a C\$33.5 million grant from Canada First Research Excellence Fund (CFREF)¹⁹. The institute carries out research on quantum information, materials and engineering, with training for quantum technology engineers.

Prototyping happens at the MiQro Collaborative Centre²⁰ (C2MI), a not-for-profit organisation that shares office and lab spaces between universities and industries. C2MI is designed to feed applied research into commercialisation of microelectronics. More than 60 companies use the facility, including IBM and Teledyne.

The Institut Quantique also runs the IQ Call for projects, a seed funding programme awarding up to C\$1 million to ideas put forward by institute members and collaborators – including students, technicians, research staff and professors. This targets high-impact strategic projects, which may involve new technology, partnerships, collaboration with industry or start-ups.

Sherbrooke is a member of the Institut Transdisciplinaire d'Information Quantique (INTRIQ)²¹ – a consortium of universities working on quantum information science and technology in Quebec and Ontario, which also includes McGill, Montreal and Polytechnique Montreal.

1.2.3 Vancouver

In July 2015 a CFREF award of C\$66.5 million went to the Quantum Matter Institute at the University of British Columbia (UBC). Since 2016 they have received a further funding from the university, CFI, the British Columbia Knowledge Development Fund²² and Stewart Blusson; and been renamed the Stewart Blusson Quantum Matter Institute²³ (SBQMI).

In a newly-extended building, the 18 faculty researchers aim to design novel quantum materials and exploit emergent electronic behaviour at surfaces. Collaborating with Simon Fraser University they are exploring new technologies for quantum information processing (see section on quantum computing in Section 2). What was fundamental research a few years ago is now gradually being turned into devices, with a dedicated budget for transition to industry, and a director of business development (Karl Jessen). UBC has opened one

innovation hub for start-ups in downtown Vancouver and plans another on campus closer to research facilities.

UBC has joined up with the Max Planck Institute²⁴ in Stuttgart and the University of Tokyo²⁵ to form an international centre for quantum materials²⁶ which supports exchanges, workshops and research collaborations

1.2.4 Quantum Alberta

This is a brand identity for quantum activity at the universities of Calgary, Alberta and Lethbridge, with a total of 45 researchers. These teams specialise in quantum networking using photonic interfaces, making them natural partners for the quantum information and quantum communications hubs in the UK.

This work is partly driven by an expectation that the money in quantum computing will be building algorithms to run on platforms elsewhere, so networking technology will be essential to create secure quantum cloud computing – and a secure quantum Internet of Things. In the University of Alberta, the Ultracold Atoms²⁷ group focuses on microwave-to-optical transduction, with one aim being to scale up quantum computing by coupling superconducting fridges.

1.2.5 National Research Council (NRC)

The NRC's quantum technology programme, currently known as Quantum Photonic Sensing and Security²⁸, has a C\$9 million budget and 40 researchers. They are collaborating with industry and universities to develop technology platforms and applications in quantum cyber security and photonic sensing, with a deliberate effort to spin out tech projects including single photon sources, mass spectrometer fibre sensors. Work in the Fibre Photonics Group, on structured fibres, overlaps with work in the UK, for instance at the universities of Bath, Southampton and Oxford. The NRC group also run workshops for community engagement, such as quantum sensing for mining.

1.2.6 University of Ottawa

The Centre for Research in Photonics²⁹ in the University of Ottawa has wide expertise in quantum technology, with notable strengths in bio-photonics, correlated imaging and atto-second science. The Centre is linked to the Max Planck Institute in Erlangen through the Max Planck-University of Ottawa Centre for Extreme and Quantum Photonics.

¹⁸ www.usherbrooke.ca/iq/en

¹⁹ www.cfref-apogee.gc.ca/home-accueil-eng.aspx

²⁰ www.c2mi.ca/en

²¹ www.intrinq.org

²² www2.gov.bc.ca/gov/content/governments/about-the-bc-government/technology-innovation/bckdf

²³ <https://qmi.ubc.ca>

²⁴ www.mpi-stuttgart.mpg.de

²⁵ www.u-tokyo.ac.jp/en

²⁶ www.fkf.mpg.de/mpg-ubc

²⁷ <https://sites.ualberta.ca/~ljleblan/Lab.html>

²⁸ www.nrc-cnrc.gc.ca/eng/solutions/collaborative/quantum_photonic.html

²⁹ <https://photonics.uottawa.ca/en>

1.3 Quantum Companies

The scale of funding to support commercialisation activities from government, provinces and private donations is already showing signs of creating a critical mass of commercial quantum technology. There is a vibrant community of quantum technology start-ups, and a few larger companies including the quantum computing firm D-Wave (see case study).

Quantum software and machine learning seems to be a particular strength. For example, 1Qbit identify market opportunities for quantum computing. With a staff of about 60 people, and partnerships with firms including Fujitsu and Accenture, they recently secured C\$45 million in financing.

Some spinouts are preparing industry for the day when quantum computing breaks Rivest–Shamir–Adleman (RSA)

encryption. In Waterloo, ISARA was founded by members of the Blackberry security team and now employs 35 people in helping corporations to become quantum safe. Although ISARA is not strictly a quantum technology company as it uses classical algorithms to replace RSA, the company is interested in integrating quantum key distribution with the use of these algorithms, for hybrid encryption – a possible area of collaboration with the UK.

“The big business in quantum computing is going to come from software.”

Warren Wall, COO D-Wave

CASE STUDY

D-Wave

D::WAVE
The Quantum Computing Company™

Based in Vancouver, D-Wave has raised C\$250 million in venture capital and employs more than 170 people. D-Wave may be closer than any other organisation worldwide to achieving useful, commercially valuable quantum computation, which they estimate to be perhaps two to three years away.

The company has got this far by taking an unconventional approach. Most attempts to build a quantum computer do so by mimicking the structure of classical computers: using logic gates to manipulate information. Because qubits (quantum bits) tend to be fragile, these machines require error-correction procedures, and it may be that hundreds of physical qubits are needed to make one effective error-corrected qubit. D-Wave takes a different approach known as quantum annealing, in which qubits interact rapidly to settle into a low-energy state. The desired computation is encoded into the system of qubits and the strength of interaction between them, and the final state represents an answer. This does not require error correction.

There remain doubts about whether and where this method can give a quantum advantage over classical computers; and it cannot execute the two known quantum-gate algorithms: Shor’s algorithm (factoring large numbers) and Grover’s algorithm.

But company members are confident that it will be effective for many kinds of machine learning and optimisation problems, as well as other tasks that are reaching a point where classical computers cannot keep up. They anticipate applications in sectors including healthcare, finance, cybersecurity, aerospace and materials.

The company still depends on investment but is generating revenue. Google, Lockheed and Los Alamos labs have bought machines, the latest model selling for C\$15 million. The company is now shifting towards a cloud-based business model, selling time for C\$2,000 per hour. Even though the machines do not yet demonstrate quantum speedup, software developers are buying time in order to develop user interfaces and applications.

D-Wave is looking at a collaboration to open a quantum computing centre in Bristol.

1.4 Funding Sources

The funding landscape is complicated. Many federal agencies contribute, along with provincial governments and philanthropists.

NSERC

The Natural Sciences and Engineering Research Council³⁰ supports quantum technology research across the country.

IRAP

Within NRC, the Industrial Research Assistance Program³¹ provides support to innovative and creative SMEs, through programmes such as Eureka and the Canadian International Innovation Program. Part of its role is helping firms grow through international collaboration. They fund collaborative R&D between Canadian SMEs and their international partners, work with Global Affairs Canada and the Trade Commissioners Services to locate new partners and develop shared projects.

CIFAR

The Canadian Institute for Advanced Research³² funds two international, interdisciplinary quantum research programmes: quantum information science and quantum materials.

CFREF

The Canada First Research Excellence Fund³³ gives large awards to help institutions develop their research strengths. In quantum science and technology, three awards totalling more than C\$200 million have been granted to support facilities and programmes at the universities of Waterloo, Sherbrooke and British Columbia.

CFI

The Canadian Foundation for Innovation³⁴ has put more than C\$100 million into quantum research infrastructure.

CERC

The Canada Excellence Research Chairs programme³⁵ awards universities up to C\$10 million over seven years to support world-renowned researchers and their teams to establish ambitious research programmes at Canadian universities – for example helping the University of Ottawa to attract US researchers to its quantum programme.

Provinces

Provincial governments often make large investments in local research – for example Quebec put C\$94.9 million into Sherbrooke's C2MI innovation centre (see overleaf). It was suggested during the mission that having two tiers of government can lead to extra bureaucracy. However, quantum research institutions in the UK might do well to follow Canada's lead by better exploiting regional funding sources such as LEPs, devolved governments and the regional growth fund.

Philanthropy

Quantum research and innovation in Canada has benefited enormously from philanthropy, especially in paying for bricks and mortar – notably the Mike & Ophelia Lazaridis Quantum-Nano Centre in Waterloo, and the Stewart Blusson Quantum Matter Institute in Vancouver.

³⁰ http://nserc-crsng.gc.ca/index_eng.asp

³¹ www.nrc-cnrc.gc.ca/eng/irap

³² www.cifar.ca

³³ www.cfref-apogee.gc.ca/home-accueil-eng.aspx

³⁴ www.innovation.ca

³⁵ www.cerc.gc.ca/home-accueil-eng.aspx

2. Relative Strengths

Canada is strong in basic quantum science, especially computing and communication. Its approach is also different. The UK's approach has been more top-down, with a national programme focusing on the development of quantum technologies in specific areas, engaging with established industry, whilst encouraging entrepreneurial activity. Canada's approach is more bottom-up, focusing on quantum information science and promoting entrepreneurship around it: it is largely left to institutions to choose their own direction as the quantum technology industry finds its format and areas of early traction.

2.1 Technologies

2.1.1 Photonics

Both countries are strong in this crucial enabling technology. In 2016 photonics sector revenue in Canada was approaching C\$4.6 billion, coming from 400 companies with a total of more than 25,000 employees³⁶. UK photonics revenue in 2017 was £12.9 billion, with more than 65,000 people employed by about 1,500 companies³⁷. Canada's photonics research has many overlaps with the UK.

2.1.2 Quantum Computing

Canada is a leading nation on quantum computing research and development. Both the UK and Canada are pursuing photonics-based quantum computing, but Canada has strengths in superconducting qubits (Sherbrooke and Waterloo) and quantum annealing (D-Wave), and also engages in research on diamond spin qubits. A group at Simon Fraser University and the University of British Columbia are developing a silicon platform with infrared photonic connections, which complements work at the Oxford and York hubs where the approach is to connect spin qubits with optical links. Although at a very early stage, there is optimism that this would allow a photonic interface to qubits with a long coherence time, with applications in quantum memory, quantum repeaters and spin-based quantum computers.

Canada also has greater and more sophisticated investment in quantum software and protocols than the UK. Several software companies (see Quantum Companies) are providing consultancy and developing generic tools and prototype applications. Some suggested that the UK should reconsider its strengths and competitiveness in quantum software.

2.1.3 Quantum Communication

The two countries have complementary strengths, with fibre-based communication in the UK and space-based cryptography in Canada.

Fibre-based quantum communication networks in the UK have demonstrated world-leading performance in security, distance and key rate. Networks in Cambridge and Bristol are connected by a long-distance link via London. The Quantum Communications Hub is also working on a space Quantum Key Distribution (QKD) demonstration.

In Canada, Thomas Jennewein's group in Waterloo has explored the viability of satellite QKD for several years, testing the radiation hardness of detectors and developing a prototype, along with management systems for QKD networks. It now has funding for orbital demonstrations of QKD:

- Nano Quantum Encryption Satellite (NanoQEY)³⁸, a 16kg nanosatellite to test high-risk technologies, due for launch in 2020/21.
- Quantum Encryption and Science Satellite (QEYSSat)³⁹, a 60kg satellite with a fully functioning QKD payload.

In contrast to China's Micius QKD satellite⁴⁰, the Canadian systems will place the photon detectors on the satellite, with photon sources and quantum memory on the ground.

³⁶ http://photonscanada.ca/media/67747/cpic-report-en-15_feb_2016.pdf

³⁷ <https://ktn-uk.co.uk/press/photronics-worth-12-9b-to-the-uk-economy>

³⁸ <http://spie.org/Publications/Proceedings/Paper/10.1117/12.2067548>

³⁹ <https://uwaterloo.ca/institute-for-quantum-computing/qeyssat>

⁴⁰ <https://phys.org/news/2018-01-real-world-intercontinental-quantum-enabled-micius.html>

2.1.4 Sensing

There is some research on quantum sensing in Canada, for example at the NRC in Ottawa and the IQC in Waterloo, but the UK is stronger in this area.

The UK National Quantum Technology Sensors and Metrology⁴¹ hub has a strong focus on cold-atom sensing and timing for space, which includes:

- The Cold Atom Space Payload (CASPA)⁴², a CubeSat technology demonstration mission due to fly in 2020/21.
- A plan for a fully functional orbiting cold-atom gravity imaging system.

There are striking parallels between this programme and Canada's plans for space QKD, with a clear opportunity for a collaborative programme in space-based quantum technology.

2.1.5 Imaging

The UK is strong in this area. In Canada there is relatively little imaging activity, although research at the University of Ottawa on ghost imaging corresponds closely with some of the more fundamental work of the Quantum Enhanced Imaging Hub⁴³ (Robert Boyd on the Canadian side and Miles Padgett from the UK are collaborators).

2.2 Turning Research into Innovation

In the UK, the hub system is focused on making devices, whereas in Canada there still seems to be a priority for quantum science over technology.

However, aspects of the Canadian system may be better for innovation in the long run. One participant preferred the overall structure for innovation in Canada. They clearly define the roles of academia, industry, funders and government, then fill any gaps with bridging organisations such as Velocity Garage (below). In the UK, academics are under pressure to exploit and gain impact from research, meaning that people may not be doing activities best suited to their expertise.

The collaboration model at the IQC (companies on one floor of the building, with IP protected) may allow better engagement with the academic community than the alternative models – potentially attractive for innovation centres in Phase II of the UKNQTP.

2.3 Infrastructure

Large, well-equipped and well-designed purpose-built facilities in Waterloo, Ottawa and Vancouver impressed many UK representatives. These “big shiny new buildings” have evident physical advantages, for example providing low-vibration quiet rooms, and siting fabrication facilities right next to quantum researchers. It can also help attract and retain talent, and aid in networking between academics and industry. Much of this has been funded through philanthropy.

2.4 Skills, Training, Recruitment and Knowledge Transfer

Both countries recognise the urgent need for more skilled personnel, particularly quantum engineers.

The UK National Quantum Technology Programme (UKNQTP) includes three centres for doctoral training (Quantum Engineering in Bristol; Controlled Quantum Dynamics at Imperial College London; and Delivering Quantum Technologies at University College London). There are three training and skills hubs in Quantum Systems Engineering at Imperial, UCL and Bristol/Cranfield.

While there are no precisely equivalent quantum-technology training centres in Canada, the country does have very effective general mechanisms for student industrial training, notably Mitacs (see case study) and the co-op model. In a co-op⁴⁴, PhD students do an internship every year. In the UK's current doctoral training programmes, this happens only in the first year Masters component. The co-op model can take the mystery and fear out of going into business.

Insights from discussions included a sense that traditional academic career paths may be a poor fit for this fast-moving field, with PhD programmes that take five-to-seven years to finish by which time you are outdated; and that training for quantum personnel should include leadership and project management. Research groups in Canada are increasingly looking for talent abroad. For example, the University of Ottawa set up a C\$25 million fund to attract international researchers.

2.5 Entrepreneurship

Canada seems to be ahead of the UK in entrepreneurial capabilities and support with organised programmes such as Creative Destruction Lab (see case study) which bring mentors and investors together with creative young people. Canadian start-ups have attracted large amounts of funding: D-Wave, 1Qbit and Xanadu⁴⁵ have raised hundreds of millions of pounds collectively, comparable to the whole UK government investment.

⁴¹ www.quantumsensors.org

⁴² <http://gtr.ukri.org/projects?ref=EP%2FR002525%2F1>

⁴³ <https://quantic.ac.uk>

⁴⁴ <https://coop.uottawa.ca/en/future-students/how-coop-works>

⁴⁵ www.xanadu.ai

CASE STUDY

MITACS



Mitacs is a national organisation that provides skills development and industry experience for graduates through internships, studentships and secondments. They are funded by central and regional government.

The Mitacs model has similarities with Innovate UK's Knowledge Transfer Partnership scheme, but with a four-month unit of student engagement that can be multiplied according to project needs. Interns may stay with a company for several years, and larger projects can involve as many as 150 internships. Costs are shared fifty-fifty between Mitacs and the sponsoring company. Academic supervisors must be involved to support the project, and each intern is mentored within the company.

Mitacs is open for international collaboration, allowing exchanges between Canadian universities and UK companies, UK universities and Canadian companies, or between university research groups.

We heard from companies in Vancouver that Mitacs internships had been very important for them ("a phenomenally successful experience"), and that they often give interns permanent jobs. One attraction is the simplicity of the scheme, with a minimal admin burden.



CASE STUDY

Creative Destruction Lab



The Creative Destruction Lab is a programme for massively scalable science and technology start-ups, with the goal of creating C\$100 billion in equity by 2027. It is not an accelerator or incubator, but rather a structured marketplace for investors and companies. CDL provides seed funding to help start-ups to develop their business plans, but they see their main role as injecting high-quality judgement.

After an initial technical assessment, start-ups are invited to “fellows meetings” with experienced entrepreneurs-turned-angel-investors, who attend at their own expense. One-on-one meetings with mentors are used to hone ideas, followed by group meetings to provide peer-reviewed entrepreneurial advice, and potentially investment. MBA students help the start-ups with their business development.

CDL started in 2012 at the University of Toronto. In the past eighteen months branches have opened up, based in business schools at British Columbia, Calgary, Montreal, Halifax and New York University (the first outside Canada). Much of their finance is provided by alumni of each business school. The programme recruits globally and provides relocation and visa application support packages.

Some of their start-ups derive from PhD research, helped by the fact that the University of Waterloo allow inventors to own their IP, whereas in the UK some rights may be retained by universities. CDL does not take any equity or IP.

In 2017, CDL started their Quantum Machine Learning Programme, which provides free access to D-Wave and Rigetti quantum computing platforms. With this early bet on quantum software they aim by 2022 to produce “more well-capitalized, revenue-generating quantum machine learning software companies than the rest of the world combined”.

“When we came to CDL, people were incredibly well informed, asking all the right questions and finding all the weak points in our business so quickly that it was a relief”

Sarah Morgan, CEO NanoLit

2.6 Industrial Engagement

The UK quantum technology ecosystem includes large companies such as Toshiba, Airbus and BT. By contrast the quantum community in Canada is struggling to get real engagement from Canadian big industry. The mission saw no engagement from mining or oil and gas companies, although Barry Sanders (University of Calgary) said that these sectors are now gaining an interest in quantum technology.

There are links with big US companies, including Amazon and Google, thanks to initiatives such as the AI and digital superclusters. The physical presence of these companies in Waterloo and Toronto, and consequent networking, means they might be first in line to benefit from developing quantum technologies.

Market Opportunities

Canada has large mining, oil and gas industries that are looking for disruptive technologies. This is a customer base the UK quantum community could tap into, for example with quantum gravity sensors to detect holes, magnetometers to measure the susceptibility of rocks, and portable quantum clocks for precise time-stamping of data.

Quantum-enabled secure communication systems and services will find markets in several different sectors.

Both countries can supply components and services to each other's growing quantum technology research and innovation sector – for example the Canadian programme in space-based QKD should be an opportunity for UK firms to build ground stations and components such as transmitters and entangled photon sources, while the four Canadian groups working on diamond-spin qubits are a potential market for the UK as it has a lead in diamond growth.

2.7 Culture and Diversity

Canada may benefit from a culture of directness. According to Sarah Morgan of NanoLit⁴⁶, asking brutally honest questions can help a business get past its roadblocks; but in the UK, people often shy away from such direct criticism. Innovation Commissioner Alan Winter explained how British Columbia got industrial commitment to the Digital Supercluster by visiting companies and asking directly: what would the supercluster need to look like for you to invest 10% of your R&D budget?

Both sides noted the lack of diversity among UK mission participants. In general Canada seems to be ahead of the UK in encouraging inclusion and gender balance: factors that are considered likely to increase innovation.

2.8 Outreach

Outreach, communication and teaching are high priorities in Canada. They seem very accomplished at this and resource it well. Early engagement and teaching stimulate next generation teachers and scientists, and it is vital to have well-articulated messages to government, funders and potential partners.

Several organisations are involved in outreach to an even greater degree than the UK QT Hubs. IQC spend C\$2 million per year on outreach, targeting students, educators, graduates and undergraduates. For example, UseQIP is an undergraduate school for 30-35 students, many of whom are then accepted for a three-month placement at IQC. The institute has also created a quantum exhibition, which has toured six Canadian cities and is going international in 2018.

⁴⁶ www.nano-lit.com

3. Future Collaboration

The mission found a genuine appetite for long-term and meaningful collaboration, from foundational science through technologies in space, security and defence, to standards, training and entrepreneurship.

3.1 A Grand Challenge

A popular idea to galvanise the quantum technology effort in both countries was to pursue one or more grand challenges. A grand challenge should lie at the intersection of the capabilities of the UK and Canada. Possible grand challenges suggested during the Expert Mission include:

- Transatlantic entanglement. Linking UK and Canadian QKD fibre networks via space (see communications section below).
- Protein folding. Misfolded proteins are thought to be a cause of some forms of dementia, but the folding process is difficult or impossible to model with classical computers. Can we develop a quantum algorithm to do it?
- Fast low-loss optical switching. This capability would transform what is possible with optical quantum computing and would exploit the common expertise in photonics in the UK and Canada.
- Quantum radar. Has the potential to detect stealth aircraft, but practical quantum radar is a long way off.

3.2 Playing Fields

3.2.1 Standards and Certification

Industrial standards must be driven by the existence of products or close-to-market prototypes, and vendors and users must want to implement these standards. This is highly relevant to quantum communications, for which large scale networks are being built in several countries and interoperability of systems is important; and standards might soon be important for optical clocks, where networks linking different countries are envisaged. The UK and Canada are already collaborating on QKD standards through participation in the ETSI Industry Specification Group on Quantum Key Distribution⁴⁷.

NRC, NPL and NIST are setting up a working party on developing standards for quantum technologies. As well as

quantum communications, this will cover other technologies including clocks, sensors and other devices, and the associated components such as ion and atom traps and compact lasers.

3.2.2 Communications

Quantum communications may be the most promising channel for technical collaboration. There are existing collaborations to build on, and UK and Canadian expertise in fibre and space-based quantum communications are complementary.

A future global quantum network is likely to comprise national fibre networks, for which links of several hundred kilometres are possible, and either fibre-based quantum repeaters or satellites for longer links. Given that Canada will soon launch a quantum enabled satellite, QEYSSat, it would be fruitful to collaborate on the interfaces between satellite and land-based fibre networks.

This could form a grand challenge – a programme to connect the York QKD network to the Alberta QKD network using the Waterloo satellite system. This literal quantum link between the countries would be an ambitious, long-term goal. In the near term we could focus on stepping stones towards it. Participants suggest that the UK could build a ground station for QEYSSat, and a transmitter for inclusion in the spacecraft.

A smaller but vital step would be working to make systems interoperable, by taking components from networks in one country to test how they work on networks in the other.

Both sides suggest collaborating on quantum safe communication: developing systems of infrastructure and software that are secure from the threat of a quantum computer breaking RSA, by combining quantum cryptography and quantum resistant algorithms. This will mean designing QKD into systems today as an alternative way of establishing cryptographic keys.

⁴⁷ www.etsi.org/technologies-clusters/technologies/quantum-key-distribution

3.2.3 Sensing in Space

While Canada is forging ahead with space-based QKD, the UK is working on space-based cold-atom sensors. These two programmes could be a good fit. It may make sense, for example, to launch the UK's CASPA alongside Canada's NanoQEY. This could be bracketed with collaboration on QKD under a "Quantum Space" heading, as the opportunity for a collaborative programme for quantum in space that will yield world leading results is astonishingly strong.

3.2.4 Computing

There are groups working on silicon qubits in Waterloo and Vancouver, representing a good opportunity for the UK to collaborate given its relevant skills base. Warren Wall at D-Wave expressed an interest in working with UK researchers on universal quantum annealing. NPL has indicated its interest in collaborating with Canadian groups on factors limiting scaling in quantum computers.

3.2.5 Supply Chains

Both countries are using the same critical components for common technologies, with lots of replication in supply chains. This could be consolidated, with a shared and agreed engineering wish list for suppliers to deliver against. For suppliers that would mean more critical mass; for academics and engineers it would reduce replication.

In the same way shared training, workshops, reports and manuals would cut replicated effort in the education of end users — we don't both have to prepare material on why clocks might be important for GPS resilience.

Annex 1

List of UK Participants

M-Squared Lasers⁴⁸

National Physical Laboratory⁴⁹

Oxford Instruments NanoScience⁵⁰

Toshiba Research Europe⁵¹

Element Six Group⁵²

Kelvin Nanotechnology⁵³

Airbus Defence and Space⁵⁴

Teledyne e2v⁵⁵

York Quantum Communications Hub

Glasgow Quantum Imaging Hub

Birmingham Quantum Sensors and Metrology Hub

Oxford Networked Quantum Information Technologies Hub

Innovate UK

Knowledge Transfer Network (KTN)

⁴⁸ www.m2lasers.com

⁴⁹ www.npl.co.uk

⁵⁰ www.oxford-instruments.com

⁵¹ www.toshiba.eu/eu/Toshiba-Research-Europe

⁵² www.e6.com

⁵³ www.kelvinnanotechnology.com

⁵⁴ www.airbus.com

⁵⁵ www.e2v.com

Annex 2

Abbreviations

CERC	Canada Excellence Research Chairs
CFI	Canadian Foundation for Innovation
CFREF	Canada First Research Excellence Fund
CIFAR	Canadian Institute for Advanced Research
CSA	Canadian Space Agency
CSE	Communications Security Establishment
DRDC	Defence Research and Development Canada
IQC	Institute for Quantum Computing
IRAP	Industrial Research Assistance Program
JQI	Joint Quantum Institute
KTN	Knowledge Transfer Network
NRC	National Research Council of Canada
NSERC	Natural Sciences and Engineering Research Council
QKD	Quantum key distribution
QSTAC	Quantum Security Technology Access Centre
QT	Quantum Technology
UKNQTP	UK National Quantum Technologies Programme



