Quantum Potential

Expert Panel on the Responsible Adoption of Quantum Technologies

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COUNCIL OF CANADIAN ACADEMIES
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The Council of Canadian Academies (CCA) acknowledges that its Ottawa offices are located on the unceded, unsurrendered ancestral home of the Anishinaabe Algonquin Nation, who have cared for the environment of this territory for millennia. Though our offices are in a single location, our work to support evidence-informed decision-making has potentially broad impacts across Canada. We at the CCA recognize the importance of drawing on a wide range of knowledges and experiences to inform policies that will build a stronger, more equitable, and more just society.

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Expert Panel on the Responsible Adoption of Quantum Technologies

Under the guidance of its Scientific Advisory Committee and Board of Directors, the CCA assembled the **Expert Panel on the Responsible Adoption of Quantum Technologies** to undertake this assessment. Each expert was selected for their expertise, experience, and demonstrated leadership in fields relevant to this assessment.

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The CCA also recognizes the contribution of **Stephanie Simmons,** Associate Professor, Simon Fraser University; Chief Quantum Officer, Photonic Inc. (Coquitlam, BC)

Message from the President and CEO

Throughout the 20th century, physicists developed the theory of quantum mechanics, spurring technological advances that gave rise to the Information Age. Now, an emerging class of innovative technologies is applying the rules of quantum mechanics to the myriad ways in which we handle information itself. Quantum technologies hold transformative potential for a range of sectors, including healthcare, pharmaceuticals, scientific research, telecommunications, manufacturing, and defence. The coming years will determine just how transformative they prove to be.

Canada benefits from a robust quantum research landscape and has prioritized the production and commercialization of quantum technologies. Still, as quantum technologies develop, there remain critical opportunities for Canada to explore a responsible approach to their adoption and anticipate a variety of attendant concerns, from information security to social acceptance. While widespread adoption of quantum technologies may remain a distant prospect, their potential ramifications — for national security, economic prosperity, and public safety — require early and sustained consideration.

Quantum Potential details the opportunities and challenges posed by quantum technologies. It evaluates the conditions that might enable broad access to quantum technologies in Canada, as well as evidence and knowledge concerning their responsible adoption.

I am grateful to the members of the expert panel, led by Raymond Laflamme, for their vital contributions to Canada's quantum readiness, and to the policy preparations that will shape it.

Eric M. Meslin, PhD, FRSC, FCAHS, ICD.D
President and CEO, Council of Canadian Academies

Message from the Chair

Humans are curious. This curiosity inspires us to observe nature and develop theories to understand the world. These theories not only describe known physical phenomena but also predict new ones. Once understood, it is possible to turn passive observations into active control and make the phenomena work for us, leading to new technologies. These can have a multitude of impacts and even change the fabric of society itself. Additionally, they can allow for the creation of tools that enable us to push our curiosity in novel directions, starting a new cycle of discovery and innovation. We can only wonder what natural phenomena will characterize such cycles in the future.

In the 20th century, research into the physics of quantum mechanics produced a revolution in technologies — lasers, transistors, magnetic resonance imaging — that underpin our modern world. We are now experiencing a *second quantum revolution* in quantum computing, communications, and sensing that may have even greater impact. However, significant scientific and engineering challenges remain, and the economic impact of quantum technologies will likely be concentrated, at least in the near term, in specific sectors. Although prototypes and early applications are beginning to emerge, widespread commercialization and adoption of quantum technologies are likely still many years off.

Nonetheless, now is the time for policy attention. It is still early enough to shape the development and impact of these technologies, but the window of opportunity will soon close. International interest and investment in the potential of quantum technologies are escalating, and Canada's early leadership is at risk. The *National Quantum Strategy* released in 2023 is an important step to boosting quantum technology production and commercialization in Canada. However, in order to realize the full potential of these technologies, deliberate policy interventions are necessary to ensure their adoption by end-users. Greater emphasis will also be needed on addressing the ethical, legal, social, and policy challenges created or exacerbated by the adoption and use of quantum technologies.

I wish to extend my sincere thanks to every member of the expert panel, all of whom gave generously of their time for this important project. Their expertise, respectful engagement, and hard work helped produce a thorough and timely report. I would also like to thank the peer reviewers, whose anonymous feedback helped strengthen the report. On behalf of the entire expert panel, I would like to thank the CCA staff for their dedication and support throughout the process of this assessment.

It is my vibrant hope that this report motivates and supports a comprehensive, forward-looking approach to realizing Canada's quantum potential.

Raymond Laflamme, O.C., FRSC
Chair, Expert Panel on the Responsible Adoption of Quantum Technologies

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Peer Review

This report was reviewed in draft form by reviewers selected by the CCA for their diverse perspectives and areas of expertise. The reviewers assessed the objectivity and quality of the report. Their confidential submissions were considered in full by the expert panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring panel and the CCA.

The CCA wishes to thank the following individuals for their review of this report:

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The peer review process was monitored on behalf of the CCA's Board of Directors and Scientific Advisory Committee by **David A. Wolfe,** Professor, Political Science, University of Toronto Mississauga; Co-Director, Innovation Policy Lab, Munk School of Global Affairs and Public Policy, University of Toronto. The role of the peer review monitor is to ensure that the panel gives full and fair consideration to the submissions of the peer reviewers. The Board of the CCA authorizes public release of an expert panel report only after the peer review monitor confirms that the CCA's report review requirements have been satisfied. The CCA thanks Dr. Wolfe for his diligent contribution as peer review monitor.

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Unnamed officials of the Canadian Security Intelligence Service (CSIS)

Executive Summary

The world is currently experiencing a *second quantum revolution*. Quantum technologies have undergone a decades-long evolution, from theoretical concept to practical technology. This evolution involves ongoing and accelerating improvements in capabilities, reductions in cost, and an increasing variety of potential and novel applications. Quantum technologies offer the opportunity to harness the properties of quantum mechanics in order to expand the boundaries of what is possible. For instance, quantum sensing could be capable of measurements of unprecedented precision; quantum communications promise to improve the security of transmitted and stored data; and quantum computing could impact all aspects of information technology and optimize many processes, including supply chain management, manufacturing, and distribution of resources (e.g., water, energy).

In 2023, the Government of Canada released its *National Quantum Strategy* (NQS), which aims to strengthen the domestic quantum ecosystem by investing in programs that support scientific research, talent development, and technology commercialization. When quantum technologies become commercially available, they could have applications across a broad range of sectors — including chemistry and materials science, healthcare, defence, finance, manufacturing, natural resources, pharmaceuticals, scientific research, space, and telecommunications — creating significant micro- and macroeconomic benefits for individual industries and the Canadian economy as a whole.

However, as with other technologies, quantum-enabled solutions bring a number of risks that could negatively affect the lives of people in Canada. For example, the use of quantum technologies (including available quantum/classical hybrids) by malicious actors could undermine the digital infrastructure that underpins key areas of everyday life, jeopardize data privacy and security, and exacerbate the digital divide.

Recognizing the rapid growth of the domestic and international quantum ecosystem, Innovation, Science and Economic Development Canada (ISED), the National Research Council of Canada (NRC), and three other supporting federal departments[1] (hereafter, "the sponsor") asked the CCA to convene an expert panel tasked with identifying and assessing the opportunities and challenges attached to the adoption of quantum technologies in Canada. To answer the charge, the CCA assembled a multidisciplinary and multi-sectoral panel, the Expert Panel on the Responsible Adoption of Quantum Technologies ("the panel"), whose members have backgrounds and expertise in quantum science, business development, ethics, economics, law, and public policy.

1 The Canadian Space Agency, Defence Research and Development Canada, and Transport Canada.

Answering the Charge

In light of current trends affecting the evolution of quantum technologies, what opportunities and challenges do these present in Canada?

Scientific and engineering obstacles currently impede the commercialization and adoption of most quantum technologies. Although existing quantum computing prototypes have scientific value and promise some computational advantage, large-scale quantum computing is unlikely to reach technological maturity in the next 10 years. Similarly, in the domain of quantum communications, quantum key distribution (QKD) needs to overcome significant limitations on distance, speed, and cost to reach the commercialization stage. In the near term, most efforts to strengthen the security of communications against decryption by quantum computers will likely prioritize classically based quantum-resistant cryptography (QRC). Among the different quantum technologies, sensors may be the closest to commercialization and adoption, but they still face a number of technical and cost-related challenges.

In light of these trends, any estimates that forecast the adoption timelines and economic benefits of quantum technologies are still speculative and can contribute to a hype narrative. While hype is not inherently bad (e.g., it can help drive research and development), a failure of quantum technologies to deliver on exaggerated or sensationalist promises could undermine public trust in innovation, reduce research funding, and deter end-users from adopting solutions that can be beneficial for their organizations. The extent to which the economic potential of commercially available quantum technologies is realized in Canada depends on the adopting sectors. Some sectors often cited as early adopters (e.g., pharmaceuticals, chemistry) make relatively small contributions to Canada's gross domestic product. To better realize the economic potential of quantum technologies, diffusion and adoption strategies could target the applications of quantum in sectors of particular economic importance to Canada, such as natural resources and healthcare.

In addition to offering economic benefits, quantum technologies could enhance the security of infrastructure and data, improve the precision of measurements, and optimize and simulate various processes. QRC and quantum sensors — two technologies that are closer to commercialization — have applications in various sectors, including finance, healthcare, pharmaceuticals, and telecommunications. The main function of QRC (and QKD) in any sector is protecting the security of stored and transmitted data from decryption by a future quantum computer. The opportunities offered by quantum sensors, on the other hand, depend on their applications in different industries. They can be used, for example, to develop navigation systems for submarines (defence), to detect soil conditions (agriculture), to monitor the integrity of infrastructure (energy), and to detect and identify underground deposits without drilling or excavation (mining; oil and gas). The purported benefits of quantum computing lie in its ability to optimize and simulate processes and predict events. For example, quantum computers can be used to run simulations that could help researchers understand chemical reactions and design better catalysts, to optimize logistics and supply chain management in the transportation and defence sectors, and to develop more accurate predictictions and recommendations in the healthcare and finance sectors.

What are the enabling conditions to ensure broad access to and market readiness for quantum technologies in Canada?

International dependencies and the scarcity of components and materials can create bottlenecks in the path to market readiness for quantum technologies in Canada. Some raw materials (e.g., Rubidium-87, Calcium-43, Barium isotopes, Helium-3) and manufactured components required to fabricate quantum technologies (e.g., specialized nanofabrication and microfabrication techniques and materials, cryogenic devices) are scarce and can only be obtained from a handful of foreign suppliers. While a roadmapping process can help identify potential bottlenecks in the path to commercialization, the provenance of certain components or materials is unknown in some cases. International co-operation is instrumental in securing the supply chain for the production of quantum technologies in Canada. Domestic production of components used in many quantum technologies (e.g., photonics devices) could give Canadian quantum companies some leverage in global supply chains and international partnerships.

Quantum hubs encompassing small- and medium-sized enterprises (SMEs), business support services, and research institutes have emerged in British Columbia, Alberta, Ontario, and Quebec. They can rely on a number of technology transfer strategies — the sale or licensing of intellectual property, the establishment of companies, and the transfer of personnel from academia to industry — to advance the market readiness of quantum technologies. Promising technology transfer practices, however, are difficult to identify due to a lack of quantitative and qualitative data assessing their effectiveness. Moreover, clustered distribution of quantum expertise can lead to regional disparities. Some regions do not have quantum hubs and are absent from the commercialization pillar of the NQS. This can frustrate the diffusion of technologies across the country and exacerbate inequities among regions and communities.

What are the main socioeconomic, regulatory, and ethical challenges related to the adoption of quantum technologies in Canada?

The adoption of quantum technologies involves a number of interrelated ethical, legal, social, and policy implications (ELSPI). The panel analyzed these implications through an approach (Quantum ELSPI) that takes a pro-innovation stance on quantum technologies and seeks to maximize benefits and mitigate risks related to their adoption, which presents both new and familiar challenges. For example, the potential for quantum computing to decrypt frequently used encryption systems presents privacy and national security risks on a scale never seen before. Malicious actors could use quantum computers to hack personal data and compromise the security of the infrastructure underpinning important societal functions, such as healthcare, financial, and industrial systems. Even if quantum technologies are used solely for legitimate purposes, some actors may exploit the inherent scientific complexity of quantum mechanics to facilitate the spread and public acceptance of misinformation about quantum technologies. This may erode public trust, limit research funding, slow the evolution of quantum technologies, and stifle technology adoption by end-users.

Some existing social and ethical challenges will be exacerbated by quantum technologies' ability to optimize familiar processes, including surveillance, automated decision-making, and natural resource mining. To the extent that quantum-enabled automated decision-making systems are trained on bad data, they may amplify discriminatory practices against underrepresented and racialized people and groups. Moreover, quantum-enhanced scrutiny and contextualization of information about people (also known as the process of sensemaking) can minimize privacy protections and optimize machine-learning instruments that commodify personal data. Finally, some types of quantum sensing present risks to privacy due to their ability to conduct remote searches and public surveillance. Privacy law may protect people against some forms of quantum-based surveillance, but legal reforms will be necessary to address the heightened risk of the identification of previously anonymized data (i.e., data re-identification) for the purposes of predictions, surveillance, and decision-making.

Limited access to quantum technologies can amplify the digital divide among people, regions, and countries. Big technology firms are establishing their dominance in the quantum sector, particularly in quantum computing, by acquiring smaller firms or offering quantum computing as a service. The concentration of quantum computing in the hands of only a few companies may lead to access disparities between economically advantaged and disadvantaged groups, and among users in different countries and regions of the world.

The abuse of market power by large quantum companies located in foreign jurisdictions is particularly relevant for Canada, whose economic growth relies on SMEs. Prohibitive costs and a lack of expertise prevent domestic SMEs from adopting innovative technological solutions to grow their business. Canada's competition policy as well as various protections afforded by intellectual property law may enable major market players to achieve and maintain their dominance in the quantum sector, creating obstacles for Canadian SMEs willing to adopt quantum technologies.

A responsible approach to the adoption of quantum technologies within the framework of Quantum ELSPI consists of state-sanctioned and self-regulating measures that anticipate, prevent, and mitigate harms and risks. This approach draws on a historic analysis of policy responses to other innovations having a systemic impact on society (e.g., semiconductors, artificial intelligence, nuclear technology, nanotechnology), while recognizing the unique properties of quantum technologies. It aims to engage stakeholders, civil society, and international partners in the adoption process, and to address central aspects of that adoption, such as public perception, public trust, and regulatory gaps. Resulting measures and guardrails could include quantum impact assessments (comparable to algorithmic impact assessments), reforms to data protection and privacy law, balancing equitable and controlled access to certain quantum technologies, soft law mechanisms, and responsible research and innovation (including public engagement and education campaigns).

What does the current evidence and knowledge suggest regarding promising and leading practices that could be applied to drive and accelerate the adoption of quantum technologies in Canada?

Canada's innovation policy has historically prioritized the supply side of the innovation process, minimizing the importance of demand-side strategies for technology diffusion and adoption by industry. In the domain of emerging technologies such as quantum, policies tend to prioritize supply-side instruments to a greater extent due to a relatively small number of technology applications and end-users. The adoption of quantum technologies by the public and private sectors may require policies and programs designed to stimulate the demand for innovation (Figure 1). These can include public-private co-operation (including government procurement and other specialized programs, as well as public-private partnerships), regulation, pro-competition oversight and policies, industry-led initiatives, and building a quantum-ready workforce for the adopting sectors. These instruments enable the government to determine the direction of innovation policy and use it to address ethical, socioeconomic, legal, and governance issues.

Driving and Accelerating Adoption

Funding
- Government procurement
- Specialized programs and agencies

Planning and leadership
- Industry associations
- Triple-helix model
- Roadmapping
- Sector-specific/government advisory boards

Considerations
- Regulatory intervention
- Competition
- International technology standards
- Quantum-ready workforce
- Education
- Immigration

Figure 1 Levers to Stimulate the Adoption of Quantum Technologies

Evidence shows that **government procurement** is an important policy instrument to incentivize the adoption of new technologies, but existing procurement programs aimed at innovative SMEs are underutilized and do not meet their spending objectives. In addition to procurement, **specialized government programs and agencies** could facilitate the uptake of quantum technologies in various sectors. The experiences of foreign jurisdictions such as Finland and Germany demonstrate that technology diffusion is the key mandate of successful government programs. Moreover, the potential of government initiatives is contingent upon building strong inter-firm consortia and integrating advanced end-users into technology diffusion networks. Foreign jurisdictions leading in the quantum space (e.g., European Union, United States) are developing specialized **industry associations or consortia**. Domestically, Quantum Industry Canada unites both producers and users of quantum technologies to, among other things, facilitate the commercialization and adoption of quantum technologies by Canadian companies.

Hybrid cross-sectoral organizations involving governments, industry, and academia (also known as the **triple-helix model**) have been successful in facilitating technology adoption in some foreign jurisdictions, including Germany and the Netherlands. Such cross-sectoral collaborations can help identify applications for, and accelerate the adoption of, quantum technologies in specific sectors and help raise awareness of the ELSPI aspects of technology adoption across multiple stakeholders. In Canada, collaborative efforts among academia, industry, and government in biomanufacturing and life sciences could serve as a model for a domestic approach to cross-sectoral partnerships in quantum technologies.

National as well as sector- and technology-specific **roadmaps** can help stakeholders identify and address various challenges impeding the adoption and commercialization of quantum technologies. In the panel's opinion, the roadmapping process is one of the most promising technology adoption strategies contained in the NQS. The experiences of foreign jurisdictions (e.g., Australia, Germany, the Netherlands, United Kingdom, European Union) show that the development of national roadmaps usually involves different orders of government and focuses on opportunities for collaboration among stakeholders in the private sector and academia.

Another public-private collaborative approach to encouraging the uptake of quantum technologies is a **sector-specific or government advisory board** that facilitates discussions among various stakeholders — developers, users, governments, and academia. While government advisory boards (e.g., Quantum Advisory Council in Canada, National Quantum Initiative Advisory Committee in the United States) tend to prioritize quantum technology development, alternative models could focus on technology adoption by providing financial assistance to co-operative projects designed by sector-specific boards to, among other things, develop adoption-supporting technological capabilities and infrastructure. This could help identify sector-specific strengths and weaknesses and cultivate relationships among stakeholders within the sector.

Quantum technology companies may implement some industry-led approaches to facilitate technology adoption. These include business-to-business partnerships among technology producers and end-users and the provision of professional support services (e.g., cloud-based quantum computing, education and training, customized applications). A key advantage of this approach is that it gives new or inexperienced end-users access to specialized technology and expertise in a cost-effective way, thereby promoting open innovation.

Many sectors often cited as potential adopters of quantum technologies (e.g., finance, telecommunications, mining, healthcare) are subject to federal and provincial/territorial regulation. Various **regulatory interventions**, including cybersecurity standards and data privacy rules, may incentivize the adoption of quantum technologies that ensure regulatory compliance. Policies that confer too much discretion on the administrative state, however, could have unintended chilling effects on privacy and human rights. Moreover, regulation cannot substitute for the important role of **competition** in driving quantum technology adoption. In sectors with high levels of vertical integration, such as telecommunications, pro-competition policy reforms and regulatory oversight could have a spillover effect that helps drive the adoption of quantum technologies.

In order to sell technologies internationally and embed themselves in global supply chains, domestic companies must comply with **international technology standards**. The lack of standardization is inhibiting the adoption of QRC. In some cases, select countries and the private sector can influence the standards-setting process to advance the international adoption of national or company-specific standards. A coordinated domestic approach is instrumental in ensuring Canada's meaningful participation in international standards-setting forums.

Even though a variety of programs and instruments can stimulate the diffusion and adoption of quantum technologies, evidence demonstrates significant shortages in a **quantum-ready workforce** for both developing and adopting sectors. This shortage is likely to increase with the development of new applications and use cases, but there is a lack of reliable projections on personnel needs. Training and education as well as immigration are two complementary strategies to prepare, attract, and retain highly qualified personnel.

When it comes to **education**, training in quantum technology is largely offered at the graduate level. While some positions in the quantum industry require a PhD, many others (including engineers, software developers, and technicians) do not. A variety of alternative education and training opportunities (including programs offered at the undergraduate and college levels, work-integrated learning, programs for senior executives in the adopting sectors, and hands-on industry training) can be considered when designing educational curricula. Information about skills needed in the adopting sectors could inform industry-focused programs. Strategies for developing a quantum workforce would benefit from prioritizing the recruitment of groups currently underrepresented in quantum-related disciplines (and in science, technology, engineering and math more broadly).

Canada also depends on **immigration** to build its quantum-ready workforce. Existing programs for foreign workers and international students (e.g., Global Talent Stream, Canadian Experience Class, Provincial Nominee Program) can help attract and retain talent. Foreign-trained workers and international students, however, face a number of immigration-related obstacles, such as a lack of National Occupational Classification codes for quantum-based occupations, high tuition fees, immigration processing backlogs, and onerous study and work permit fees. Canada's Express Entry program does not account for a variety of work experiences acquired by international students during their studies, thereby creating systemic barriers to international graduates seeking permanent residency. As an alternative, flexible and agile immigration programs, similar to ones that fuelled the development of the telecommunications sector in the 1990s, could give Canada a leg up when competing for the international talent necessary to stimulate technology adoption and shape quantum innovation on a global level.

Abbreviations

AUTM	(formerly) Association of University Technology Managers
BDC	Business Development Bank of Canada
BERD	business enterprise expenditure on R&D
CDL	Creative Destruction Lab
CERN	European Organization for Nuclear Research
CETA	Canada-European Union Comprehensive Economic and Trade Agreement
CRTC	Canadian Radio-television and Telecommunications Commission
CSIS	Canadian Security Intelligence Service
CSTAC	Canadian Security Telecommunications Advisory Committee
CTI	Canadian Training Institute
CUSMA	Canada-United States-Mexico Agreement
DARPA	Defense Advanced Research Projects Agency (U.S.)
DIQKD	device-independent quantum key distribution
DND	Department of National Defence (Canada)
EPO	European Patent Office
GNSS	global navigation satellite systems
GPT	general purpose technologies
HPC	high-performance computing
HQP	highly qualified personnel
IDEaS	Innovation for Defence Excellence and Security
IRAP	Industrial Research Assistance Program
ISED	Innovation, Science and Economic Development Canada
ISTAR	intelligence, surveillance, target acquisition, and reconnaissance
MIMO	multiple input / multiple output
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration (U.S.)

NCC	National Cybersecurity Consortium
NISQ	noisy intermediate-scale quantum
NIST	National Institute of Standards and Technology (U.S.)
NMR	nuclear magnetic resonance
NOC	National Occupational Classification
NQS	National Quantum Strategy
NRC	National Research Council Canada
NSA	National Security Agency (U.S.)
NSERC	Natural Sciences and Engineering Research Council of Canada
NV	nitrogen-vacancy
OECD	Organisation for Economic Co-operation and Development
OPM	optically pumped magnetometer
OSFI	Office of the Superintendent of Financial Institutions
PNT	positioning, navigation, and timing
PPP	public-private partnership
PQC	post-quantum cryptography
QCaaS	quantum computing as a service
QED-C	Quantum Economic Development Consortium (U.S.)
QEYSSat	Quantum Encryption and Science Satellite
QIC	Quantum Industry Canada
QKD	quantum key distribution
QML	quantum machine learning
QRC	quantum-resistant cryptography
QTEdu CSA	quantum technology education coordination and support action
Quantum ELSPI	ethical, legal, social, and policy implications of quantum technologies
QuaST	quantum-enabling services and tools for industrial applications
QuIC	European Quantum Industry Consortium
SME	small- and medium-sized enterprise

SQUID	superconducting quantum interference device
TCS	Trade Commissioner Service (Canada)
UKRI	UK Research and Innovation
USPTO	United States Patent and Trademark Office

Discussing quantum technologies requires a level of understanding of quantum science; therefore, most discourse about quantum technologies is undertaken by experts in the field using language that can be hard for non-experts to follow. A list of key terms has been developed to complement the abbreviations noted here, which provides non-technical and non-rigorous descriptions of some of the quantum-specific concepts found in the report (p. 174). For a technical glossary, the reader is encouraged to refer to Ezratty (2021) and Hoofnagle and Garfinkel (2021).

Contents

1

Introduction

Quantum technologies hold great potential for innovation and commercialization in computing, communications, and sensing, which can in turn affect a wide range of economic sectors. Many countries are making substantial investments in their quantum ecosystems, building leadership and competitiveness. Canada, a leader in quantum science, is facing both opportunities and challenges in the implementation, adoption, and social acceptance of quantum technologies.

1.1 History of Quantum Technologies

Early in the 20th century, physicists believed they had a solid understanding of how the physical world functioned. Using classical theories inherited from luminaries such as Isaac Newton and James Clerk Maxwell, physicists thought that nearly all laws of the physical world could be accounted for. Lord Kelvin is often attributed as saying: "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." However, some phenomena remained unexplainable using classical theories, such as why a heated piece of metal glows red, why atoms can be stable, and why some atomic nuclei undergo radioactive decay. For these phenomena, classical theories fail spectacularly. To explain them, a new theory had to be created: *quantum mechanics*.

1.1.1 The Theory of Quantum Mechanics

The theory of quantum mechanics was developed in the mid-1920s and used concepts that were anathema to classical physics, such as the ideas that energy comes in discrete, *quantized* packages, that matter simultaneously exhibits particle- and wave-like behaviours, and that there is some probability that matter will *tunnel* (i.e., appear in places that would be impossible to explain with classical physics). Quantum theory asserts that a fundamental randomness is at the heart of all measurements — an idea that still challenges human intuition and classical ways of thinking. The theory of quantum mechanics led to the *first quantum revolution* and, ultimately, allowed for the development of technologies that have had a tremendous impact on society, such as atomic clocks, lasers, transistors, light-emitting diodes (LEDs), electron microscopes, and magnetic resonance imaging (MRI) (Dowling & Milburn, 2003; Jaeger, 2018). These technologies underlie nearly all modern electronics and computing and enabled the development of the current information age (Dowling & Milburn, 2003; Jaeger, 2018).

However, there is another quantum effect that has not yet been utilized: *superposition*. In classical physics, a particle can be here *or* there, but the superposition principle of quantum mechanics asserts that particles can be here *and* there. This led Albert Einstein and his colleagues Boris Podolsky and Nathan

Rosen to claim that the theory was incomplete (Einstein *et al.*, 1935). Furthermore, to question the puzzling and counterintuitive consequences of the superposition principle, in 1935 Erwin Schrödinger proposed that the superposition of states of atoms (i.e., excited or not excited) can be magnified to a state where a cat is simultaneously both dead and alive (Schrödinger, 1935). In the 1940s and 1950s, debates about the implications of quantum mechanics were thought to be more philosophical than real. Then, in the 1960s, John Bell looked at the properties of the state of superposition of two systems together and turned these surprising ideas into a mathematical equation (now known as a Bell inequality) that could be verified by experiments. His approach used the correlation — that is, the statistical dependencies between the measurements of two particles — predicting one result if the experiment behaved classically, and another if the experiment behaved quantum mechanically.

In October 2022, the Nobel Prize in Physics was awarded to Alain Aspect, John Clauser, and Anton Zeilinger for a series of experiments demonstrating the violation of Bell inequalities, and thus the failure of classical physics (Aspect *et al.*, 1982). The implication of these experiments is that the microscopic world does not obey the rules of the classical world. Particles can be in a superposition of states called *quantum entanglement*, which cannot be understood from a classical perspective. This has implications for how we interpret reality and how the world fundamentally works. This brief discussion of the history of quantum mechanics leaves out many important contributions, including those from underrepresented groups, some of whom are described in Box 1.1.

Box 1.1 The Contributions of Women and Underrepresented Groups to Quantum Science

Conspicuously missing from traditional accounts of the early history of quantum mechanics are the contributions of women, racialized researchers, and researchers outside Europe and North America. Despite systemic barriers and inequities in research and educational opportunities, these scientists made important contributions to the development of the field. For example, Canadian physicist Laura Chalk performed the first experiments that confirmed Schrödinger's theory of wave mechanics. Wu Chien-Shiung, well-known for her groundbreaking

(Continues)

(Continued)

parity-violation experiments, was the first to measure clear evidence of the correlations between entangled pairs of photons. Lucy Mensing found that the quantum numbers associated with orbital angular momentum were integers. In India, C.V. Raman performed light-scattering experiments that provided convincing early proof of quantum theory and earned the 1930 Nobel Prize in Physics for his Raman effect. Highlighting these and many other contributions by researchers of all backgrounds not only tells a more complete history of quantum mechanics but also lays the foundation for developing a diverse and inclusive quantum science and technology community.

1.1.2 Quantum Information Science

At the same time as these first experiments in quantum entanglement were being performed, physicists and mathematicians were pondering how quantum mechanics could impact information processing. In 1980, Paul Benioff showed how quantum mechanical systems could be used to compute reversibly but underestimated the extra computational power these new rules allowed (Benioff, 1980). Yuri Manin (1980) and Richard Feynman (1982) are credited with first understanding that quantum computers would be able to perform computations that classical computers could not, suggesting that quantum computers would be ideal for simulating quantum systems. Since then, many more applications for quantum computers have been identified beyond the field of physics and chemistry, with potential impacts in fields such as drug design, economic forecasting, and much more.

Until the 1990s, quantum computers were mostly of interest to academics investigating the fundamental limits of computation. But in 1994, Peter Shor developed a quantum algorithm that could factor numbers that are a product of primes (Shor, 1994). Although this problem seems rather esoteric at first glance, such algorithms are the foundation of today's internet encryption, which is based on the difficulty of factoring primes. The quantum community was surprised when Shor showed that a quantum computer, if one could be developed, could easily break nearly all existing encryption schemes, having implications ranging from personal privacy to national security.

It was originally thought that quantum computers would be so sensitive to environmental noise that it would be impossible to build them (Haroche & Raimond, 1996) or have sufficient control over them to perform any useful computations (Landauer *et al.*, 1995). Fortunately, *quantum error correction* was discovered (Shor, 1995; Steane, 1996), which allows quantum computers to be reliable and efficient despite the presence of noise in the surrounding environment, referred to as *fault tolerance*. Implementing quantum error correction in devices is one of the biggest challenges today and will require on the order of millions of qubits (the quantum equivalent of classical computing bits). In the coming years, achieving a fault-tolerant quantum computer is a key priority in the field.

The first experimental demonstrations of quantum computer prototypes occurred in the late 1990s (Monroe *et al.*, 1995; Nakamura *et al.*, 1999). The race was then on to gain sufficient control of the prototype to scale up. In the mid-2000s, a Canadian start-up developed quantum computing hardware based on a different paradigm known as *quantum annealing*, which utilizes quantum dynamics to tackle complex optimization problems. The first annealing quantum computers became commercially available in 2011 (Popkin, 2016). In the mid-2010s, many large companies — including Amazon, Google, IBM, and Microsoft — started to develop quantum computer prototypes.

In recent years, a variety of organizations around the world — including Google in the United States, the University of Science and Technology of China, and Xanadu in Canada — claimed to have reached a so-called *quantum advantage*; that is, using a quantum computer to solve a problem that a classical computer would be unable to feasibly solve (Arute *et al.*, 2019; Zhong *et al.*, 2020; Madsen *et al.*, 2022).[1] While some of these claims have been contested — in 2022, a research team demonstrated that the problem solved by Google's quantum computer could in fact be solved using ordinary computer processors, and that existing supercomputers could solve the problem even faster than the quantum computer (Pan *et al.*, 2022). These experiments showed a path toward scalability and are seen as milestones for quantum information science, even though they solved rather contrived problems whose applications appear to be useful only to demonstrate quantum advantage. Scaling to larger devices will be necessary to make quantum computers robust to noise and solve problems that have societal benefits.

While many researchers were thinking about quantum computers, physicists were analyzing the relevance of quantum mechanics for communications and cryptography. Around 1970, Stephen Wiesner demonstrated that it might be possible, using the rules of quantum mechanics, to make money that could not be counterfeited (Wiesner, 1983). This was the first indication that quantum mechanics could have an impact on cryptography. In 1984, Charles Bennett and Gilles Brassard

1 Some sources use the term *quantum supremacy* and others *quantum advantage* when describing a quantum computer outperforming a classical computer. This report uses the latter due to the negative associations with the term *supremacy* (Palacios-Berraquero *et al.*, 2019).

proposed a scheme that would come to be called *quantum key distribution* (QKD), which guarantees that an encryption key cannot be copied and allows for the detection of eavesdroppers (Bennett & Brassard, 2014).

As indicated above, the Achilles' heel of quantum computers is their extreme sensitivity to noise. However, scientists have cleverly turned this problem into an asset by designing quantum devices that utilize this property for sensing (Caves, 1981). It has been demonstrated that these devices can surpass even the best theoretical sensitivity of classical sensing devices. Quantum sensors have the potential to impact a large number of areas where increased sensitivity would be useful, such as metrology, natural resources extraction, healthcare, and more.

1.1.3 The Second Quantum Revolution

The *second quantum revolution*, a term coined by Jonathan Dowling and Gerard Milburn (Dowling & Milburn, 2003), refers to the development of technologies that use the rules of quantum mechanics for storing, manipulating, and transmitting information. The technology that will emerge in the second quantum revolution is, importantly, different from that which was developed in the first:

> *[First-generation quantum technologies] are essentially based on the properties of large ensembles of quantum particles and possibilities for controlling them … The emerging second generation of quantum technologies … is based on something completely new: the directed preparation, control, manipulation, and subsequent selection of states of* individual quantum particles *and their interactions with each other* [emphasis in original].
>
> Jaeger (2018)

The second quantum revolution is not simply about the development of quantum computers; rather, it has opened the door to many other applications of quantum technologies. Quantum sensing and quantum communications can harness quantum properties to achieve incredibly precise measurements and secure communications, respectively, while quantum cryptography (and quantum-resistant classical cryptography) will allow for greatly enhanced data security. These technologies are likely to have myriad applications in different sectors and may be among the first commercially available quantum-related technologies that are widely adopted (Green *et al.*, 2021).

Recognizing the potential value of quantum technologies, a growing number of diverse industries have begun to explore how they could be adopted, while governments have begun to develop strategies to prepare for the opportunities and challenges presented by quantum technologies. As Paul Davies stated in 1997, "the nineteenth century was known as the machine age, the twentieth century will go down in history as the information age. I believe the twenty-first century will be the quantum age" (Davies, 1997 as cited by Jaeger, 2018).

1.2 What Is Different about Quantum Technologies?

On the surface, quantum technologies may seem comparable to any other emerging technology, such as nanotechnology and artificial intelligence (AI). But in the view of the panel, quantum technologies are fundamentally different because of their perceived ability to operationalize the principles of quantum mechanics. Quantum mechanics, despite being "arguably the most accurate physical theory," is also "deeply counterintuitive" (Barrett, 2019). The implications of quantum mechanics are difficult to explain to non-specialists because they are only fully described through mathematic formalisms, which do not lend themselves to human intuition (Albert, 1992). Full descriptions of quantum mechanics require that people abandon their familiar assumptions about the nature and behaviour of material objects and instead think in terms of mathematical arguments (Barrett, 2019).

To understand the difference between classical and quantum information science, it is necessary to make a short foray into *complexity theory*, the part of computer science that assesses the resources required to solve a problem relative to the problem's *size*. For example, in multiplication, the size of a problem is the number of digits of the numbers being multiplied. A fundamental question of complexity theory asks how many resources (e.g., bits, operations, energy units) are needed to solve a problem as it increases in size. Computer scientists have divided the set of problems into two classes: easy problems and hard ones. The resources needed to solve easy problems scale polynomially with the size of the problem, whereas hard ones scale exponentially.

To understand the impact of quantum computers, one more element is needed: the *strong Church-Turing thesis*. This thesis claims that different computers can only solve problems in the same complexity class using, at most, a polynomial difference of resources. In other words, if a problem is hard, it is hard for all computers. The strong Church-Turing thesis is a fundamental tenet of classical computer science. However, it turns out that the thesis comes from a classical understanding of the laws of physics. Using quantum computers, some classically hard problems become easy. This has been a fundamental surprise and the finding has generated excitement in quantum information science because it demonstrates that there are problems that might be hard or intractable with classical computers that can be tackled with quantum computers.

The second quantum revolution is based on quantum information science, which investigates how to use the rules of quantum mechanics to manipulate information. At first glance, it appeared these rules could be a hindrance. In fact, in the late 1970s, Bennett apparently asked Feynman whether the theory of quantum mechanics puts a fundamental limit to computation; Feynman found that there was no such limit (Feynman, 1982). Moreover, not only is there no such limit, but the last 40 years have shown that, at least theoretically, using quantum mechanical rules leads to a surprising advantage for information processing. The coming years will show whether this theoretical advantage of quantum computing can be turned into a practical advantage to solve problems of societal relevance — an advantage that has already materialized with quantum sensors.

1.3 The Charge to the Panel

Recognizing the need to better understand the opportunities and challenges associated with the adoption of quantum technologies in Canada, Innovation, Science and Economic Development Canada (ISED), the National Research Council of Canada (NRC), and three other supporting federal departments[2] (referred to collectively as "the sponsor") asked the CCA to convene an expert panel to answer the following questions:

In light of current trends affecting the evolution of quantum technologies, what opportunities and challenges do these present in Canada?

- What does the current evidence and knowledge suggest regarding promising and leading practices that could be applied to drive and accelerate the adoption of quantum technologies in Canada?
- What are the enabling conditions to ensure broad access to and market readiness for quantum technologies in Canada?
- What are the main socioeconomic, regulatory, and ethical challenges related to the adoption of quantum technologies in Canada?

2 The Canadian Space Agency, Defence Research and Development Canada, and Transport Canada.

1.4 The Panel's Approach

The CCA assembled a multidisciplinary and multi-sectoral panel of experts (the Expert Panel on the Responsible Adoption of Quantum Technologies, hereafter "the panel"). Panel members were selected for their knowledge of physics, law, innovation, ethics, finance, and business. The panel met six times in person and via videoconference between May 2022 and July 2023 to deliberate on the charge, collect and review evidence, discuss implications, and refine report drafts. The final report reflects the panel's consensus based on its assessment of the evidence.

This report was also informed by a comprehensive peer review process, whereby additional experts provided further evidence and guidance. External peer review provided feedback to inform the panel's deliberations, and reviewers remained anonymous until after the report was finalized. This process was overseen by an independent peer review monitor from the CCA's Scientific Advisory Committee.

To support the integrity of the assessment process, panel members are required to disclose to the CCA and fellow members any conflicts of interest — actual, foreseeable, or perceived — relevant to the issues discussed, to ensure transparency. They must also abide by a confidentiality agreement and code of conduct designed to support an environment that fosters effective and respectful deliberations, is conducive to the free exchange of knowledge, and supports the assessment of evidence.

To maintain the panel's independence, sponsors do not appoint panel members, nor do they engage with the panel during the assessment process, with the following exceptions: (i) at the panel's first meeting, at which time the sponsors are invited to present the charge, and (ii) at a final briefing on findings scheduled *after* the panel has formally signed off on the report and prior to its public release, at which time the Chair of the panel presents the main findings to the sponsors.

1.4.1 Sources of Evidence

The panel's assessment was based on a review of diverse sources of evidence, including peer-reviewed publications and grey literature (i.e., policy documents, government publications and websites, as well as reports by national and international organizations and committees). The panel also engaged with guest speakers from the Canadian Security Intelligence Service (CSIS). In October 2022, the panel made site visits to two firms, D-Wave and Photonic Inc., as part of its evidence gathering. In January 2023, it hosted a session at Quantum Days 2023, a Canadian conference for quantum academics, students, and professionals, and received input from participants on topics relevant to this assessment.

1.4.2 Scope

This report focuses on issues pertaining to the commercialization and adoption of quantum technologies in Canada, such as attracting and retaining quantum talent, risks related to quantum technologies, and issues of social acceptability. Issues related to fundamental questions in quantum research, technology assessment, and comprehensive program and policy evaluation were considered out of scope.

1.5 Report Structure

Chapter 2 introduces three categories of quantum technologies — computing, communications, and sensing — and explores their commercialization potential. The chapter provides an overview of the possible economic impact of quantum technologies for select sectors in Canada that are among the most likely adopters and beneficiaries of quantum technologies. **Chapter 3** describes the quantum technology landscape, positioning Canada within the global ecosystem in terms of research activity, market activity, public policy, and the international quantum value chain. **Chapters 4 and 5** provide an in-depth review of the ethical, legal, social, and policy implications as well as the institutional and regulatory challenges associated with the adoption of quantum technologies. **Chapter 6** examines the enabling conditions and potential levers available to the public and private sectors to advance the adoption of quantum technologies. **Chapter 7** introduces a responsible approach to the adoption of quantum technologies and provides the panel's final reflections.

2

Commercialization and Adoption of Quantum Technologies

Chapter Findings

- Significant scientific and engineering challenges are currently impeding both the commercialization and adoption of quantum computing, communications, and sensing.
- Quantum computing receives the most attention and investment among quantum technologies and may represent the most significant long-term impacts and financial value. However, its near-term commercialization prospects are highly uncertain since it is furthest from technological maturity and currently lacks practical applications. The primary business model for quantum computing for the foreseeable future will likely be quantum computing as a service.
- Quantum sensors may be closer to commercialization compared to quantum computers and communications, but these will require reductions in size, weight, and cost before they are competitive with classical sensors.
- For quantum communications, a key area of focus in the near term will be implementation of quantum-resistant cryptography, with increased focus on quantum key distribution as the technology matures and overcomes existing limitations on distance, speed, and cost.
- Quantum technologies could potentially account for up to 3% of Canada's GDP by 2045, with quantum computing making the most significant contribution. The economic impact is likely to be concentrated in specific sectors. Scientific research, defence, space, chemistry and materials science, finance, and telecommunications are among the most likely sectors to be early adopters of quantum technologies.

Although some early examples of quantum technologies are commercially available and applications are beginning to emerge in various sectors, widespread commercialization and adoption are likely still years away. The potential for the commercialization and adoption of quantum technologies in Canada depends on their level of technological readiness, the economic benefits for both developers and adopters, the existence of practical applications, the improvement over existing non-quantum technologies, and the capacity of organizations to invest time, money, and resources into their adoption. Ultimately, quantum technologies will become commercially viable at a wide scale and be adopted by organizations in various sectors only after existing scientific and engineering challenges are overcome, and only when they can surpass the performance of their classical counterparts to a degree that is large enough to offset the costs incurred by switching from classical to quantum technologies. This includes not only the capital costs of procuring quantum hardware or services but also those associated with potential changes to an organization's operations, workflows, and workforce.

This chapter examines three broad categories of quantum technologies — computing, sensing, and communications — and explores their prospects for commercialization and adoption in different economic sectors in Canada, as well as their potential economic impact, over the near, medium, and long terms.

2.1 Commercialization Potential

Canada's quantum research output and industry are both heavily focused on computing, followed by communications and sensing (Sections 3.1 and 3.2). This aligns with a 2020 survey of quantum stakeholders in Canada from academia, industry, and government that rated quantum computing as the most important technology for Canada, followed closely by quantum communications, with quantum sensing rated a more distant third (Doyletech Corporation, 2020).

2.1.1 Computing

There is a general consensus that computing attracts the most attention and investment among quantum technologies (SSAC, 2022) and may present the most significant opportunities, impacts, and market potential (QDNL, 2020). However, it also has a very high degree of uncertainty and its technological maturity is unlikely to occur in the near term (Crane *et al.*, 2017; Gartner, 2019; SSAC, 2022).

One factor contributing to the uncertainty surrounding commercialization timelines for quantum computers is the diversity of technical approaches. Whereas all classical computers rely on the same basic underlying physical principles for computation, quantum computers include a wide range of different approaches to creating and manipulating quantum information (Nurminen *et al.*, 2022; QED-C, 2022b). Quantum annealers and gate-based quantum computers utilizing either superconducting qubits or trapped ions are leading in technological maturity and may become more widely available in the near term (NASEM, 2019). Other kinds of quantum computers — including those based on photonics, spin qubits, neutral atoms, and topological quantum computers — may gain greater prominence in the medium or long term (NASEM, 2019; Biondi *et al.*, 2021; Bobier *et al.*, 2021).

In the near term, most commercial applications of quantum computing are likely to be based on a hybrid classical-quantum model (Biondi *et al.*, 2021; IBM, 2022a) in which much of the computational work to solve a problem is carried out on classical computers, with the quantum computer playing only a limited role in solving one aspect of the problem (Crane *et al.*, 2017; Krelina, 2021). Indeed, because quantum computing is useful only for a narrow range of computational problems that cannot be feasibly solved by classical computers (Dekate *et al.*, 2021), it will not replace classical computing for many applications (IBM, 2022a). Moreover, even for problems where quantum computing outperforms classical computing, the former is likely to require some form of hybrid processing (IBM, 2022a).[3]

Quantum computing may lack practical applications before the emergence of error correction

Quantum computing is currently in what is referred to as the NISQ (noisy intermediate-scale quantum) era (Preskill, 2018). NISQ computers are vulnerable to environmental noise that interferes with their computational processes, producing errors. Controlling for noise in quantum computers — referred to as *error correction* — is key to advancing the field and achieving scalability. Achieving *fault-tolerant* quantum computers would be a significant milestone (NASEM, 2019; Bobier *et al.*, 2021). There is a general consensus that demonstrating quantum advantage for practical applications will require fault-tolerant quantum computers capable of error correction (Temme *et al.*, 2022; Kim *et al.*, 2023; Mandelbaum, 2023). Indeed, while there are many practical applications for fault-tolerant, error-corrected quantum computers, "practical applications for NISQ computers do not currently exist" (NASEM, 2019).

One promising approach in the near term is focusing on error *mitigation* rather than error correction — a collection of tools and methods that can produce relatively accurate, noise-free solutions for certain types of computational problems with varying levels of accuracy, even for NISQ computers (Steffan, 2022; Temme *et al.*, 2022). For example, researchers have demonstrated that an error-mitigating quantum computer can verifiably solve a complex simulation problem more accurately than state-of-the-art classical methods of approximation implemented on a supercomputer, and *might* be able to outperform other exact classical computation methods that rely on brute-force calculation (although this could not verified) (Kim *et al.*, 2023; Mandelbaum, 2023). Importantly, however, this research does not demonstrate quantum advantage because it does not show that a quantum computer can solve a problem that is infeasible (or impossible) for a classical computer to solve, nor does it show that a quantum computer can

3 In a sense, all quantum computing can be considered "hybrid," insofar as classical computers will always be required to control quantum computers. However, this should be distinguished from the sense of "hybrid" described above, in which a significant part of a computational problem is carried out using classical computers, with quantum computers being used to address a specific part of the problem.

outperform the capabilities of classical computers (Kim *et al.*, 2023; Mandelbaum, 2023). However, it does potentially suggest that quantum computers "can provide a computational advantage for useful problems before the full realization of error correction" (Mandelbaum, 2023).

Adoption of quantum computing is limited by technological uncertainty and a lack of demonstrated advantages over classical approaches

Quantum computing operates on fundamentally different principles than those of classical computing, requiring a new paradigm to be developed before a quantum advantage can be realized (Meige *et al.*, 2022). Potential users, for example, need to know (i) whether quantum computing can be used to solve their organization's problems; (ii) how to formulate a question that can be answered on a quantum computer, then interpret the answer; and (iii) how to test, integrate, monitor, and maintain quantum computing hardware and software. This uncertainty regarding the practical applicability of quantum computing is compounded by the lack of demonstrated economic advantages over classical computing. The Quantum Economic Development Consortium (QED-C), an industry consortium of quantum technology companies in the United States, points out that:

> *Quantum computing will only be useful when it can surpass the performance of the very best classical methods for a given computational problem. And it cannot merely be marginally better. It must be dramatically better if organizations are to incur the significant switching cost and potentially dramatic changes to commercial, industrial, and government workflow required to migrate from classical to quantum computing processes.*
>
> QED-C (2022b)

Additionally, uncertainty over which qubit architectures will emerge as dominant may be encouraging a wait-and-see approach, particularly for SMEs, at least until a compelling business case is made for quantum adoption. Application benchmarks that measure the performance of different quantum computing technologies for specific tasks in real-world use cases — and that enable comparisons between quantum and classical computers — will thus be particularly important to facilitating adoption by end-users (Langione *et al.*, 2022).

The development of performance benchmarks for quantum computers is ongoing and involves private sector firms, public sector organizations, industry groups, and academic researchers, often working in collaboration. For example, the Quantum Benchmarking program run by the Defense Advanced Research Projects Agency (DARPA) in the United States is currently developing benchmarks that measure progress on specific computational challenges, hardware requirements to achieve specific functions, and other practical considerations; both private sector companies and universities are involved in this initiative (QCR, 2022c; Altepeter, n.d.). In addition, QED-C has published a suite of open-source performance benchmarks for quantum computers (SRII, 2021; QED-C, 2023a).

In the near term, the primary market will likely be quantum computing as a service

The market for quantum computers themselves (i.e., hardware) is expected to be relatively small, such that only governments and large corporations are likely to purchase quantum computing hardware, specialized for particular applications (Crane *et al.*, 2017), at least in the near term. In part, this is due to the current limited utility of quantum computers, the technical challenges associated with their operation and maintenance, and the likelihood of rapid obsolescence of early models (Gartner, 2022). Economic factors also play an important role; in 2020, the cost of a classical bit was on the order of one-millionth of a cent, whereas the cost of a physical qubit was around US$10,000 and the cost of a logical qubit was estimated to be over US$1 million, and likely between US$10 to 100 million (Swallow & Joneckis, 2021).

As a result, for the foreseeable future, the primary market for quantum computers is likely to be in *computing as a service*. Vendors that offer quantum computing as a service (QCaaS) provide organizations with access to quantum computing hardware and algorithms to address specialized problems (Gartner, 2022; WEF, 2022a). However, even QCaaS is unlikely to achieve widespread commercial adoption in the near term. Nonetheless, this approach allows adopting companies to off load the upfront expense of a dedicated quantum computer and avoid the need to make space for, service, and maintain what are currently very large, complicated, and delicate devices. Notably, some cloud platforms currently providing QCaaS offer access to several different quantum computing hardware and software solutions from a variety of providers, even if they also offer their own hardware (QCR, 2022a).

A cloud-based quantum computing commercialization strategy comes with its own considerations. These bear some resemblance to those related to high-performance computing (HPC), including ownership and maintenance of the computers and supporting infrastructure; allocation of potentially limited computing time; and the availability and uptime of the computing infrastructure. In addition, there are concerns about potential secondary uses of user data (Inglesant *et al.*, 2016). In the panel's view, there will also be a need to ensure that cloud-based access to quantum computing can eventually be unchaperoned both to improve third-party access and to avoid exacerbating the digital divide in quantum computing (Section 4.3.2). Moreover, users will need to be aware of potential challenges common to cloud-computing platforms, such as communication latency between their end and the cloud; the data security and privacy protocols used by their service providers; and waiting times associated with multiple users (Gartner, 2022). However, both the hardware and software side of cloud-based quantum computing will need to advance considerably before many of these issues become relevant to users. Other challenges include data residency and data sovereignty, which concern the jurisdictions in which cloud-based data are physically stored and applicable law (GC, 2018); indeed, cloud-based quantum computing providers in some foreign jurisdictions are already trying to address these issues by basing their infrastructure in the same jurisdictions as their users (NQCC, 2022).

There is interest in quantum machine learning, but it is in its early stages and there is currently no proof of quantum advantage

Quantum machine learning (QML) broadly refers to the integration of quantum computing with machine learning. QML may offer the possibility of faster data analysis, easier processing of larger, higher-dimensional datasets, useful generalizations from a relatively small amount of training data, and lower energy requirements compared to classical machine learning (Hoofnagle & Garfinkel, 2021; Cerezo *et al.*, 2022). Some sources have suggested that QML may have one of the greatest long-term impacts among quantum technologies (Hoofnagle & Garfinkel, 2021).

However, QML is in a relatively early stage of development (Gartner, 2021b; Hoofnagle & Garfinkel, 2021). Although there are some examples of QML algorithms that can reduce the number of steps required to solve certain problems — thereby demonstrating a form of quantum "speedup" (Biamonte *et al.*, 2017) — there is currently no proof of quantum advantage for QML (i.e., outperforming classical machine learning or solving problems that classical machine learning is unable to solve) (Gartner, 2021b; Cerezo *et al.*, 2022), nor is there consensus on whether it will eventually outperform classical machine learning (Hoofnagle & Garfinkel, 2021). QML also faces a number of technical challenges, such as problems with data input (e.g., encoding classical data into quantum states that are amenable to QML processing) and data output; effects of noise that can disrupt or skew QML processing; and a lack of high-quality quantum datasets for training QML models (Biamonte *et al.*, 2017; Cerezo *et al.*, 2022).

The clearest near-term applications of QML — and the best candidates for demonstrating quantum advantage — involve simulating quantum systems in chemistry and materials science, pharmaceuticals, and high-energy physics (Biamonte *et al.*, 2017; Hoofnagle & Garfinkel, 2021; Cerezo *et al.*, 2022).

Additionally, QML may have potential applications in the defence, finance, and healthcare sectors, among others (Appendix B). It may also have applications related to quantum sensors, where QML models may help filter signal from noise (Cerezo *et al.*, 2022).

2.1.2 Sensing

Quantum sensors operate by preparing specific states of a device's quantum architecture, allowing the state to be altered by the device's environment, then using the change in the device's quantum state to infer something about what is being measured. Many of these devices have been demonstrated in-lab and in the field, but, in certain cases, are still limited by the stability and reproducibility of components, as well as gaps in fundamental science (QED-C, 2022a; CNSC, 2023; Kantsepolsky *et al.*, 2023). First-generation quantum sensing technologies, such as atomic clocks, MRI, nuclear magnetic resonance (NMR), and positron emission tomography (PET), have been revolutionary and widely adopted. Second-generation quantum sensors are now being developed and commercialized. Notably, these are in some ways precursor technologies to quantum computing and communications (Hoofnagle & Garfinkel, 2021).

Several federal government programs have already been launched to support the development and adoption of quantum sensors in Canada (ISED, 2023d). These include the Department of National Defence (DND) Innovation for Defence Excellence and Security (IDEaS) call for quantum sensing projects for defence and security (DND, 2023); the NRC Internet of Things: Quantum Sensors Challenge program (NRC, 2022b) and Quantum Photonic Sensing and Security program (NRC, 2022a); and the Innovative Solutions Canada call to support pre-commercial quantum sensor prototypes "that can be tested in real life settings and address a variety of priorities within the Government of Canada" (ISC, 2022).

Many types of quantum sensors may have near-term applications but require reductions in size, weight, and cost before they are competitive with classical sensors

Quantum sensing has been described as "the low-hanging fruit" of quantum technologies compared to computing and communications (QDNL, 2020), and may "represent some of the most promising near-term opportunities to transition quantum technologies from laboratory demonstrations to real world applications" (QED-C, 2022a). However, in contrast to other quantum technologies, "in many cases quantum sensors do not explicitly enable capabilities that are otherwise challenging or impossible to achieve using existing classical approaches" (QED-C, 2022a). Quantum sensors generally outperform their classical counterparts in three areas: they are less prone to drift (i.e., cumulative errors caused by defects and noise), they possess far greater sensitivity to changes in their environment, and they are significantly more precise in their measurements (Kantsepolsky *et al.*, 2023).

Although quantum sensors can offer a higher degree of accuracy, existing sensing technologies may be sufficient for many or even most commercial applications. Thus, while some types of quantum sensors are already commercially available, there is a consensus that widespread adoption will require reductions in size, weight, and cost before quantum sensors are competitive with classical sensors (Crane *et al.*, 2017; QDNL, 2020; Capgemini, 2022; McKinsey, 2022; QED-C, 2022a). Nevertheless, their adoption is likely to significantly increase in the near term, along with reductions in size and price, improved functionality, and identification of more use cases in various sectors (QDNL, 2020; Capgemini, 2022).

Importantly, in order to move from laboratory prototypes to commercial applications, developers of quantum sensors will need to engage more deeply with potential users in order to "understand the existing solution space and barriers to market entry, including where current sensor offerings are lacking, as well as pain points and potential size, weight, power, or cost deal-breakers for end users" (QED-C, 2022a). This can help "to ensure that sensors meet or exceed user requirements and are robust against realistic environmental conditions in areas of greatest benefits," particularly given their competition with classical sensors. However, shifting design paradigms from a "lab-in-a-box" approach to more practical and resilient designs ready for testing (and eventual deployment) under realistic operating conditions in real-world environments may be a time-consuming and costly process (QED-C, 2022a).

Additionally, quantum sensors face commercialization challenges related to their enabling technologies, such as "lasers, vacuum components, photonic integrated chips, and low-noise electronics" (QED-C, 2022a). Like sensors themselves, many types of enabling technologies will need to undergo reductions in cost, size, weight, and power requirements before they are commercially viable for real-world applications (Kantsepolsky *et al.*, 2023). Further development of enabling technologies for sensors will benefit other areas of quantum technologies, such as computing and communications (QED-C, 2022a).

Extracting data from quantum sensors is also an ongoing area of research. Raw data generated by a quantum sensor need to be extracted and transformed into useful information, which generally involves some form of big data analytics. This will require the creation of large "training" datasets, which is an ongoing challenge (Bongs *et al.*, 2023).

Quantum sensors include a wide range of technologies, and the market for different sensor types will be concentrated in different sectors

Quantum sensors encompass an assortment of diverse technologies with different levels of technological maturity, commercialization potential, and possible applications. As such, different types of quantum sensors will exhibit distinctive pathways to commercialization and adoption. Given the heterogeneity of these technologies, this section does not attempt to survey all types of quantum sensors but rather highlights some that are most frequently cited as among the leading contenders for near-term commercialization and adoption.

Atomic interferometers are a type of quantum sensor that can be used to detect and measure acceleration and rotation, as well as gravity (Crane *et al.*, 2017; QED-C, 2022a). The market is likely to be relatively small and concentrated in the natural resources extraction sector and basic scientific research. This is largely because existing sensing technology is generally sufficient for most of the needs of potential customers outside of these markets (Crane *et al.*, 2017; QED-C, 2022a). Atomic interferometry-based gravimeters may also be used for detecting underground objects and conditions for civil engineering and defence purposes (QED-C, 2022a; Kantsepolsky *et al.*, 2023).

Nitrogen-vacancy (NV) centre diamonds have nitrogen impurities that create a quantum system within the diamond that can be excited by environmental conditions, which can then be measured optically (QED-C, 2022a). They are used for sensing inertial motion as well and various types of and have applications in quantum computing and various types of microscopy (QED-C, 2022a). NV centres may also be used in NMR spectroscopy, where they could improve the current NMR spatial resolution from the millimeter scale to the micrometer or nanometer scale, with applications in chemistry and materials science, healthcare, pharmaceuticals, and manufacturing (Allert *et al.*, 2022; Liu *et al.*, 2022; Aslam *et al.*, 2023). The market for quantum-assisted nuclear spin imaging based on NV centres is likely to be primarily in health and pharmaceutical research; however, this market is likely to be relatively small in the near term, as the technology is not mature (Crane *et al.*, 2017).

Quantum inertial motion sensors are used to measure linear and angular acceleration, and may be based on atomic interferometry, NMR gyroscopes, or NV-centre gyroscopes (Crane *et al.*, 2017; QED-C, 2022a). Inertial sensors can be used as a component of positioning, navigation, and timing (PNT) systems, which may have potential applications in defence, aerospace, and autonomous vehicles, particularly when existing navigation and positioning systems such as GPS are unavailable or unusable (QED-C, 2022a; Kantsepolsky *et al.*, 2023). Crane (2017) estimates that the market for quantum inertial motion sensors used in PNT systems will be mainly in military applications, such as submarines, ships, and airplanes. Demand for quantum PNT systems may be relatively low outside of military applications, since existing PNT needs in the commercial sector — e.g., for airplanes and trucking — are largely satisfied by existing GPS technology. Furthermore, the current large physical size and high price of quantum PNT systems would have to substantially decrease (Crane *et al.*, 2017) and the prospects for miniaturization are currently uncertain (Kantsepolsky *et al.*, 2023). The arrival of autonomous vehicles could spur commercial demand, but classical PNT systems, combined with classical sensors such as radar, LIDAR, and cameras, may be sufficient (Crane *et al.*, 2017). Nevertheless, quantum imaging sensors such as single-photon avalanche diodes (SPADs) may help autonomous vehicles avoid collisions by allowing for non-line-of-sight imaging so that vehicles can "see" around corners or behind walls (Kantsepolsky *et al.*, 2023).

Quantum magnetometers are another type of quantum sensor that may be used to detect and measure magnetic fields. One type, known as a superconducting quantum interference device (SQUID), is a mature technology that has been commercially available for decades and is commonly used in medical sensing (e.g., magnetoencephalography or MEG) and natural resource exploration. However, these devices require cryogenic temperatures, limiting their portability and potential use cases (QED-C, 2022a). Thus, there is a great deal of interest in new quantum sensors known as optically pumped magnetometers (OPMs), which do not require cryogenic temperatures, are much more portable than SQUIDS, and can reduce the costs of MEG (IEC, 2021; Aslam *et al.*, 2023).

Other types of quantum magnetometers are based on atomic vapour whose atoms are excited by a laser, making them respond to magnetic fields in ways that can be precisely measured. Commercial versions of these sensors are used for detecting ships, submarines, and magnetic anomalies (QED-C, 2022a). Reducing their size, weight, and cost so they can fit on a chip is an ongoing area of research; chip-scale atomic magnetometers have applications in several sectors, including medical equipment. Other applications include geophysical surveying, security, and manufacturing, but there is currently less demand for quantum magnetometers in these sectors; their price would have to decrease before their adoption costs are offset by their benefits over classical technology (Crane *et al.*, 2017).

Atomic clocks have been commercially available since the mid-20th century, and chip-scale atomic clocks since 2011 (QED-C, 2022a). Atomic clocks are used in a wide range of commercial applications, including telecommunications, navigation, sensing, and finance, while chip-scale atomic clocks are used in oil and gas exploration. Next-generation atomic clocks based on optical transitions are currently being developed; these devices are expected to have improved performance compared to existing atomic clocks. These would most likely be used primarily in scientific research, such as physics and geology, often deployed on satellites (QED-C, 2022a).

2.1.3 Communications

Broadly speaking, quantum communications involve two related areas: (i) transmitting quantum information from one location to another, and (ii) ensuring secure communications that cannot be decrypted by a quantum computer. As to the first point, there are many potential applications for transmitting quantum information, including a *quantum internet* that could link quantum computers together; *blind* quantum computing that allows clients to remotely access a quantum computer in such a way that the vendor does not have access to their information; exchanging quantum states for cryptographic protocols; and linking quantum sensors. Importantly, these applications require *quantum networks* that allow for the exchange of qubits and the distribution of entangled quantum states across nodes in that network (Judge, 2022).[4]

As to the second point (i.e., ensuring secure communications), many applications of quantum communications relate to cryptography. This is a vast area of research and technology development that includes key distribution, encryption, digital signatures, authentications, digital currencies, and much more. As noted in Chapter 1, large quantum computers will someday have the ability to break nearly all existing encryption schemes, such as the RSA and elliptic curve cryptography algorithms that are widely used today, as well as common alternatives. To mitigate this threat, there are at least two possible options. The first is finding new classical encryption protocols that are thought to be unbreakable by quantum computers; these encryption methods are called *post-quantum*, *quantum-safe,* or *quantum-resistant cryptography* (QRC). The second option is using quantum states to establish a classical key between two parties that can then be used to exchange private information. This method is called *quantum key distribution* (QKD) and is a subset of quantum cryptography.

QKD is theoretically more secure than QRC, but real-world evidence, testing, and standards for both are lacking

QKD involves generating and sharing cryptographic keys that are then used to encrypt and decrypt messages. The distribution of these cryptographic keys uses quantum effects (e.g., entanglement, superposition of states) to ensure that no third

4 It has been suggested that quantum communications could be rebranded as *quantum networks*. However, this report uses *quantum communications* broadly to cover a variety of applications, including classically based quantum-resistant cryptography (following the conventional usage in the literature). The panel uses the term *quantum networks* in a narrower sense to refer to networks that allow for the exchange of qubits and distributed entanglement.

party can gain knowledge of the key without being detected. If an eavesdropper attempts to intercept and gain knowledge of the key, they will be detected, and the key will be discarded; if no eavesdropper is detected, the key can be used.

Importantly, QKD refers to the method of generating and sharing a cryptographic key and does not include the encryption or transmission of information. Thus, according to the U.S. National Security Agency (NSA), QKD is one component of quantum cryptography, but "is only a partial solution" because it "does not provide a means to authenticate the QKD transmission source" (NSA, n.d.). Although this characterization of QKD has been called misleading (e.g., Prisco, 2020; Renner & Wolf, 2023), it is shared by the U.K. National Cyber Security Centre (NCSC, 2020). By contrast, QRC involves the use of classical computational tools to encrypt information in ways that are thought to be secure against decryption by a quantum computer. Thus, QKD is fundamentally different from QRC.

QKD and QRC have been described, respectively, as hardware- and software-based approaches to quantum cryptography (IQT, 2019). QKD is provably secure, at least insofar as the laws of physics theoretically guarantee that a quantum key cannot be broken or copied without detection. By contrast, QRC is not guaranteed to be secure against decryption by a quantum computer (IQT, 2019), or even by a classical computer; indeed, as noted below, some promising candidates for quantum-resistant algorithms have already been broken by classical computers. Additionally, unlike QKD, it is likely impossible to prove that any given QRC protocol cannot be broken. However, although QKD is *theoretically* secure, there is no proof of such security for any real-world implementation as of September 2023, and no standards by which to test or certify security (NSA, 2021). Moreover, early implementations of QKD have been shown to be hackable in several ways, although research is ongoing to identify and mitigate these vulnerabilities (Pang *et al.*, 2020).

Cybersecurity agencies in Canada and abroad have recommended against the use of QKD in favour of QRC, at least in the near term

Some sources have suggested that QKD and QRC are not necessarily competitive, and that organizations are likely to implement the latter in the near term, followed by QKD when it becomes more widely available (Capgemini, 2022). However, the NSA has indicated that it prefers QRC and "does not consider QKD a practical security solution for protecting national security information" (NSA, 2021), "does not support the usage of QKD ... and does not anticipate certifying or approving any QKD ... security products" (NSA, n.d.). This is due to five limitations of the technology: (i) QKD is only a partial solution; (ii) it requires special-purpose equipment; (iii) it increases infrastructure costs and insider threat risks; (iv) securing and validating QKD is a significant challenge; and (v) it increases the risk of denial of service attacks (NSA, n.d.). Some have argued, however, that these are myths about QKD (e.g., Prisco, 2020).

State cybersecurity agencies in several foreign jurisdictions — including the National Cyber Security Centre in the United Kingdom (NCSC, 2020), the Federal Office for Information Security in Germany (BSI, 2020), and the National Cybersecurity Agency of France (ANSSI, 2022, n.d.) — have highlighted similar concerns about QKD and have also recommended against using it to protect sensitive information, at least in the near term; these agencies favour QRC. The Canadian Centre for Cyber Security has indicated that, while QKD may someday be a useful means for securing communications, it "is still maturing" and "is not a replacement for current applications of cryptography;" it recommends that companies develop plans to transition to QRC (Cyber Centre, 2021). However, despite the skepticism expressed by these national cybersecurity bodies, there is a great deal of interest in QKD, particularly in Europe and Asia (see below).

The adoption of QRC faces barriers related to a lack of standardization

QRC involves the use of classical computational tools to encrypt information in ways that are thought to be secure against decryption by a quantum computer. Many different types of QRC solutions are being sold by a number of companies; these are relatively low-cost, easy to implement, and compatible with existing communications protocols. However, none has been proven to be resistant to decryption by a quantum computer, and there are currently no standards against which they can be evaluated. Indeed, a significant challenge affecting the uptake of QRC is a lack of standardization. For this reason, both the Canadian Centre for Cyber Security and the U.S. Department of Homeland Security have recommended that organizations refrain from implementing QRC until standardized solutions become widely available (U.S. DHS, 2021; Cyber Centre, 2022).

In 2016, the U.S. National Institute of Standards and Technology (NIST) began work on developing standards for QRC (Alagic *et al.*, 2022); in 2022, it selected four candidate algorithms for standardization and identified four additional ones that could also be selected in the future (NIST, 2022). NIST is expected to publish the complete standards by 2024 (Alagic *et al.*, 2022). The Canadian Centre for Cyber Security is working with NIST and other partners to evaluate QRC standards, and "participating in international standards bodies including the International Standards Organization and the Internet Engineering Task Force" (Cyber Centre, 2021). (See Sections 5.4 and 6.2.3 for more on standards.) NIST has also partnered with 12 private sector companies in the United States to develop and implement quantum-resistant algorithms nationwide, with the aim of migrating to quantum-resistant cybersecurity standards by 2035 (Kelley, 2023), as per a presidential national security memorandum issued in 2022 (The White House, 2022b). Also in 2022, the United States passed the *Quantum Computing Cybersecurity Preparedness Act*, which directs government agencies to begin preparations to implement QRC by creating a prioritized inventory of information technology that may be vulnerable to decryption by a quantum computer (Gov. of U.S., 2022).

Another important challenge facing QRC lies in the fact that many of the most promising algorithms have not been thoroughly tested and could potentially be broken at some point in the future. Indeed, at least one of the four initial NIST candidate algorithms has already been cracked using a classical computer (Swayne, 2022).

There is interest in QKD in many countries, but technical challenges currently inhibit its wider commercialization

QKD is a relatively mature technology that is already in use in several proof-of-concept demonstrations, including fibre-based networks and free-space communications (Khan *et al.*, 2018). Moreover, despite the skepticism expressed by some national cybersecurity agencies (see above), there remains a great deal of interest in QKD among researchers, industry, and governments in Canada and internationally. For example, the European Union's quantum technologies strategy has prioritized widespread availability of QKD, even for consumer devices, suggesting a potentially strong international market for QKD-based products (E.U., 2016; Hoofnagle & Garfinkel, 2021). The OpenQKD project — a three-year, €15 million program that ran from 2019 to 2022 — established several QKD testbeds across Europe to test and promote QKD use cases (Hoofnagle & Garfinkel, 2021; OpenQKD, n.d.-a) and "lay the foundations for rolling out a pan-European quantum-safe digital infrastructure" (OpenQKD, n.d.-b). Furthermore, China has made significant investments in QKD, establishing a QKD network that spans thousands of kilometres and connects major cities by fibre optic links (Chen *et al.*, 2021; Johnson, 2021); it is also developing multiple QKD satellites to further expand the network (Jones, 2023). Several other countries in Europe and Asia are also actively developing QKD networks.

However, QKD faces challenges related to transmitting information over longer distances (~100 km), high costs, technical complexity, and limitations on transmission speed (Crane *et al.*, 2017; Hoofnagle & Garfinkel, 2021; Capgemini, 2022). Despite the purported security benefits that QKD offers over QRC, there has been relatively little uptake of QKD outside of government-supported testing, research institutes, and telecommunications providers (Crane *et al.*, 2017; Capgemini, 2022). Work is ongoing to mitigate these limitations; for example, one goal of the OpenQKD project is addressing practical and technical barriers to adoption, such as developing implementation standards (Hoofnagle & Garfinkel, 2021; OpenQKD, n.d.-a). QKD is expected to be more widely adopted over the next decade, particularly in the telecommunications, finance, and defence sectors, given its advantages over classical QRC; however, networks that can reach end-users likely will not be established until after 2035 or 2040 (QDNL, 2020).

Fibre-based QKD works over moderate distances but requires repeaters to boost the signal strength

Signal attenuation occurs over long-distance transmission in QKD, as decoherence occurs along the fibre path. This means the signal must be "boosted" using technology known as *quantum repeaters*. A true quantum repeater would allow for end-to-end transmission of quantum information (Wehner *et al.*, 2018). Although the theoretical underpinnings of this technology are well understood, existing technical challenges have impeded its practical development. In the meantime, trusted repeaters are used as an intermediate step in the development of long-distance QKD. They do not allow for end-to-end transmission of quantum information.

Furthermore, because of the nature of quantum information, the signal cannot be simply copied and reproduced; it must be measured (destroying the original signal), processed, and recreated each time it needs boosting, introducing security issues at the physical location of the repeater, where the signal could be intercepted. To overcome this, each repeater exchanges keys with the adjacent repeaters in a sequence of links, eventually allowing the sender and receiver to generate and share their own cryptographic key. However, each repeater in the sequence has information about that key, thereby introducing potential security vulnerabilities — thus the requirement that repeaters must be "trusted" (Wehner *et al.*, 2018).

Work on *device-independent QKD* (DIQKD) shows that it is, in principle, possible to overcome these limitations and have truly secure QKD. DIQKD even allows for the creation of cryptographic keys while using untrusted devices (Wehner *et al.*, 2018). However, there is still a large gap between DIQKD in theory and practice. DIQKD is currently in the experimental prototype phase, and is not yet close to commercialization (de Smyter, 2021).

Canada is among several countries working on satellite QKD technology

Satellite communication is another way of implementing QKD while avoiding the issues associated with fibre optic cabling. It will likely be used for long-distance QKD, while fibre-based QKD will be used for local communications networks. Canada is currently a leader in this area and is pursuing satellite-based QKD through the Quantum Encryption and Science Satellite (QEYSSat) program. Led by the Canadian Space Agency, QEYSSat is a collaborative project that includes Honeywell Aerospace and the Institute for Quantum Computing at the University of Waterloo, with nine additional collaborators at universities across Canada (including a QKD ground station at the University of Calgary) and nine additional collaborating organizations around the world (CSA, 2020; UWaterloo, 2021). Other foreign jurisdictions actively developing satellite-based QKD include China (Optica, 2022; Jones, 2023), Germany (DLR, n.d.), India (ET Telecom, 2023), Israel (QuantLR, 2021), Japan (Mamiya *et al.*, 2022), Luxembourg (Burkitt-Gray, 2021), Singapore (GW, 2019; SpeQtral, 2022), the United Kingdom (Pultarova, 2021), and the European Union (Kramer, 2022; E.C., 2023).

Quantum networks could enhance quantum computers and sensors, but they are far from technological maturity

Quantum networks — sometimes referred to as the quantum internet — are networks of quantum processors that can exchange quantum information. Quantum networks consist of three components: (i) communications channels that can carry quantum information (such as fibre optic cables), (ii) quantum repeaters that allow quantum information to be transmitted over long distances, and (iii) end nodes consisting of quantum processors (Wehner *et al.*, 2018). Among the best-known applications of quantum networks is QKD; other potential applications include distributed quantum computing, which would allow quantum computing at a scale that is currently impossible with a single quantum computer (van Dam, 2020), as well as networks of quantum sensors that could allow for extremely precise measurements.

Although quantum networking is an active area of research — for example, it is one of the central goals of a €1 billion commitment by the European Union (Quantum Flagship, 2017; Cartlidge, 2018) — it is far from technological maturity and commercial availability, and unlikely to be available before 2035 (QDNL, 2020). Nevertheless, many countries are interested in building quantum networks, including Canada (Box 2.1), and near-term investments in these networks will be beneficial to a wide range of quantum technologies over the longer term.

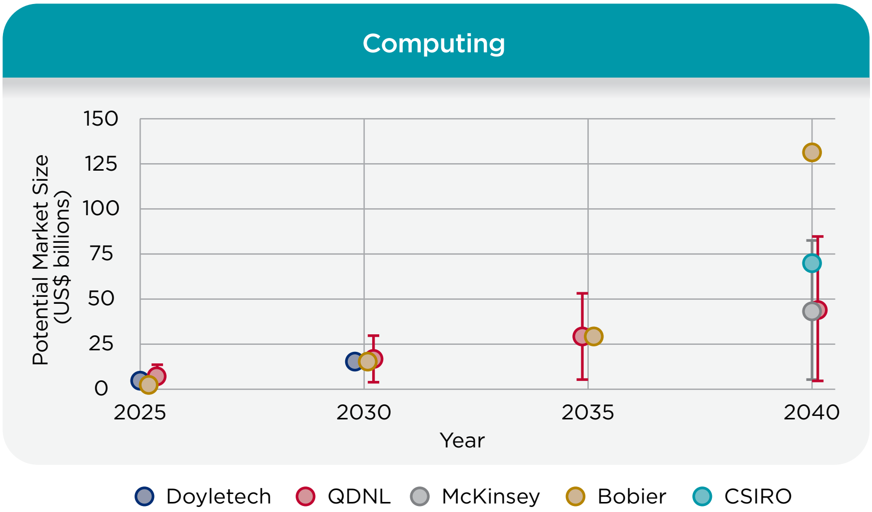
Box 2.1 A National Secure Quantum Communications Network

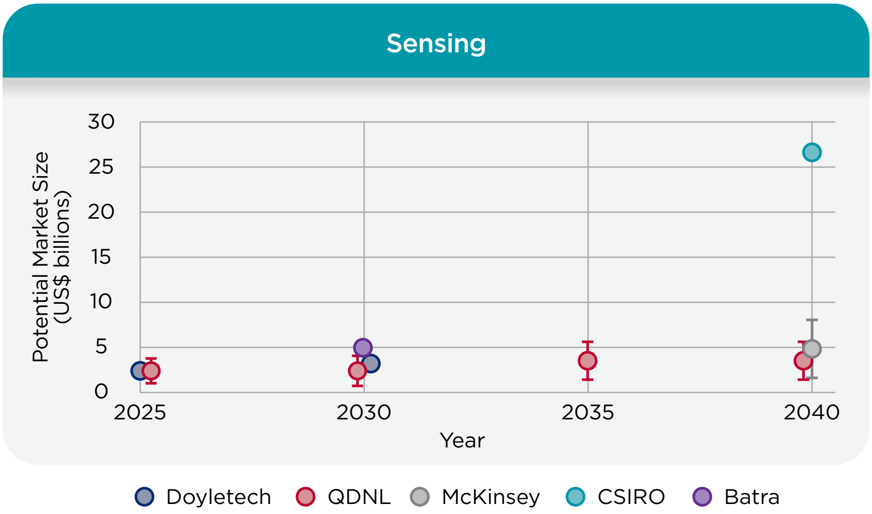
Canada's *National Quantum Strategy* (NQS) identified the implementation of a national secure quantum communications network as a key priority (ISED, 2023d). According to the NQS, there is a large commercial market tied to the secure transmission of digital information, which is highly vulnerable to emerging quantum technologies. A secure quantum communications network would incorporate quantum communications technologies as well as QRC protocols to mitigate these risks. DND has committed to developing quantum networks capable of transmitting quantum information over long distances by 2030 (DND & CAF, 2023). The NQS also identifies both land- and satellite-based infrastructure as important, pointing to QEYSSat and the NRC's High-Throughput and Secure Networks Challenge program as initiatives directed toward this goal (ISED, 2023d). However, in the panel's view, it is critical that interconnectedness be retained between national and international partners; this can be achieved if Canada is involved in the development and adoption of international standards (Sections 5.4 and 6.2.3).

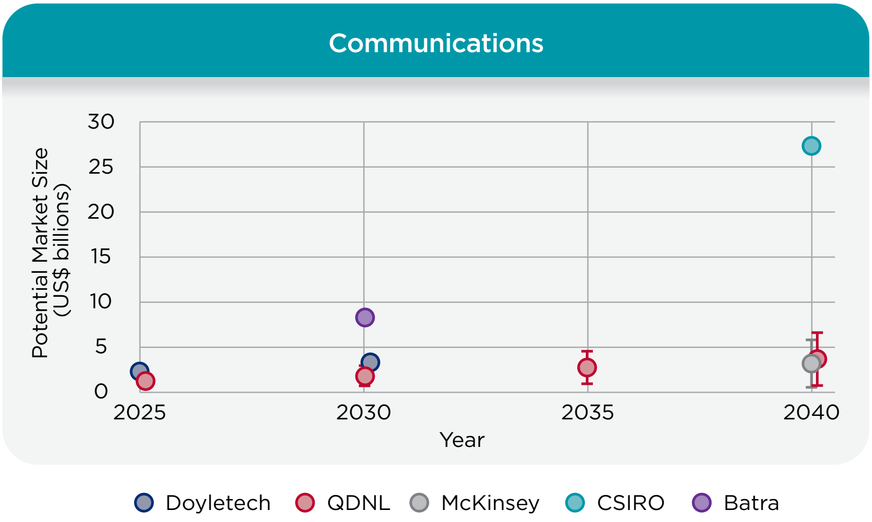
2.1.4 Potential Market Size for Quantum Technologies

Several sources (mainly, but not exclusively, consultancy firms) have attempted to estimate the potential market size for different quantum technologies and how they could grow over time (Figure 2.1). However, the panel cautions that these numbers are inherently speculative, represent rough estimates at best, and should be treated with a high degree of skepticism, as it is difficult to predict the market potential of technologies that are still years (or even decades) away from maturity, and for which few practical applications exist at the time such estimates are drawn. Indeed, in the panel's view, these numbers are likely inaccurate and exemplify quantum hype (Section 4.2.3). They are presented here simply to demonstrate the high level of uncertainty around the size and growth rate of the market for quantum technologies over the next decades. Moreover, the panel believes that focusing on market size may be myopic, as quantum technologies will undoubtedly have significant social and economic impacts across a wide range of areas.

Comparing estimates can also be difficult because various sources assess the market sizes for different sets of technologies and categorize quantum technologies in different ways. Additionally, while most estimates are presented in terms of "revenue" (Batra *et al.*, 2021; Bobier *et al.*, 2021; CSIRO, 2022), others are described as "sales" (Doyletech Corporation, 2020), "market potential" (QDNL, 2020), and "estimated market" (McKinsey, 2022); as such, it is unclear whether these estimates are directly comparable. It is also notable that estimates for the same technology from different sources can differ by as much as an order of magnitude, particularly when they are projected further into the future (e.g., 15 to 20 years). However, in all estimates, quantum computing has a much higher potential market value compared to communications and sensing, accounting for between 50% and 80% of the projected quantum technologies market over the next two decades.







Sources: Doyletech Corporation (2020); QDNL (2020); Batra *et al.* (2021); Bobier *et al.* (2021); CSIRO (2022); McKinsey (2022)

Figure 2.1 Estimated Potential Market Size for Quantum Computing, Sensing, and Communications

These figures show several different estimates of the potential market size for developers of quantum computers, quantum sensors, and quantum communications technologies. Error bars indicate estimate ranges.

Current investments in quantum technologies may provide insight into their commercialization potential

To better understand the commercialization potential of quantum technologies, it may be instructive to look at the investments being made in these technologies. Section 3.1.4 describes the size of public sector investments in quantum technologies in several countries, including Canada; importantly, however, these are not indicators of potential market size for different quantum technologies, although they do reflect their perceived economic importance. Similarly, private sector investments in quantum technologies can provide an indication of their perceived economic potential. Detailed information about investments in quantum R&D is generally not publicly available. McKinsey (2022) reports that investments in quantum technology start-ups totalled over US$1.4 billion in 2021. Moreover, between 2001 and 2021 approximately US$3 billion was invested in quantum computing start-ups, US$700 million in quantum communications start-ups, and US$400 million in quantum sensing start-ups (McKinsey, 2022), suggesting that investors expect the quantum computing market to be much larger than the markets for quantum communications and sensing.

2.1.5 Technological Readiness

Timelines for the adoption of quantum technologies depend on their state of technological readiness. Table 2.1 provides rough estimates of availability timelines for select quantum technologies. These estimates are based on a review of the literature and panel expertise. However, the panel cautions that these estimates are highly speculative, as there is a high degree of uncertainty around the state of development for many of these technologies, particularly as timelines extend into the future.

Table 2.1 Estimated Timeline for Availability of Select Quantum Technologies

	Currently Available (2023)	Emerging and Near-Term (before 2030)	Medium-Term (2030-2040)	Long-Term (after 2040)
Computing	• NISQ computing	• Early fault-tolerant quantum computing	• Fully fault-tolerant quantum computing • Quantum simulation • Quantum machine learning	• Large-scale, fully fault-tolerant, universal quantum super-computer
Sensing	• Atomic clocks • Quantum-enabled EPR spectrometers • Quantum gravimeters	• Quantum imaging • Quantum magnetometers • Quantum navigation		• Quantum radar / LIDAR
Communications	• QKD (short distance) • QRC		• QKD (long distance / satellite)	• Quantum internet

Sources: Troyer (2020); Batra (2021); Krelina (2021); Commonwealth of Australia (2021); Capgemini (2022)

2.1.6 Quantum Technologies as General Purpose Technologies

General purpose technologies (GPTs) can be broadly characterized as technologies that have "the potential for pervasive use in a wide range of sectors in ways that drastically change their modes of operation" (Helpman, 1998). One influential definition of a GPT is "a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects" (Lipsey *et al.*, 2005).

It is not yet clear whether quantum technologies are GPTs. However, addressing this question can provide insight into how pervasive and transformative they might be in the future. Notably, there has been very little discussion of this issue in the literature on quantum technologies. The World Economic Forum has implied that quantum computing is a GPT, much like the internet, electricity, and even fire (Almosallam, 2022). Similarly, Coccia (2021) claims that quantum technologies are GPTs due to their potential to make earlier technologies obsolete, support industrial and social transformation, and bring about clusters of innovations in downstream industries. That said, other sources (e.g., Dekate *et al.*, 2021) have explicitly claimed that quantum computing is *not* a GPT, insofar as it is only applicable to a narrow range of computational problems. Additionally, some have suggested that *quantum materials* are GPTs due to their "potential for major economic impact across a broad range of industries and applications" (Maine & Garnsey, 2006) (Box 2.2).

Box 2.2 Quantum Materials

Quantum materials are identified in Canada's NQS as a priority area for R&D (ISED, 2023d). These are materials that exhibit unique electronic, magnetic, or optical properties arising from quantum mechanical effects (Cava *et al.*, 2021). They can take many forms, including metals, insulators, semiconductors, and superconductors, and they can form the basis for quantum technologies. Some examples of quantum materials include topological insulators, high-temperature superconductors, and quantum dots.

There are four essential features of GPTs: (i) large scope for improvement when the technology is first introduced, (ii) a wide variety of uses, (iii) applications across large parts of the economy, and (iv) strong complementarities with other technologies (Lipsey *et al.*, 1998). First, GPTs must go through a process of evolution during which "the technology is improved, its cost of operation in existing uses falls, its value is improved by the invention of technologies that support it, and its range of use widens while the variety of its uses increases" (Lipsey *et al.*, 1998). Second, GPTs are used in a wide variety of products and processes that themselves have a wide variety of different functions. However, new GPTs typically have very few specific use cases, with new applications discovered as they evolve; thus, a GPT "has implicit in it a major research program for improvements, adaptations, and modifications." Third, GPTs can be applied in a wide range of settings across an economy; note this is distinct from them having a wide variety of uses (e.g., lightbulbs are used in a wide range of settings across an economy but have only one use). Finally, GPTs have strong complementarities with other technologies, both vertically and horizontally, such that they "cooperate with each other, either as subtechnologies within one main technology, or as separate stand-alone parts of some technology system" (Lipsey *et al.*, 1998). Such complementarities can also be characterized by an increase in R&D in downstream sectors as a result of innovation in the GPT (Bresnahan & Trajtenberg, 1995).

At least some quantum technologies arguably meet these criteria. They are, broadly speaking, undergoing what has been a decades-long evolution from theoretical concept to practical technology, with ongoing and accelerating improvements in capabilities, reductions in cost, and identification of a wide variety of new use cases in a wide range of economic sectors. Moreover, many quantum technologies have strong complementarities with other technologies, as both subtechnologies and stand-alone parts in a technology system, and they are improving innovation in downstream sectors. In the panel's view, quantum computing is likely to become a GPT, as it will likely eventually underlie and affect nearly all aspects of computing and information technology. Additionally, some aspects of quantum communications could become GPTs, such as quantum networks. However, it is far less likely that quantum sensors will become a GPT, as these technologies tend to be more specialized for particular applications, with a more limited variety of uses in fewer sectors.

2.2 Adoption of Quantum Technologies by Different Sectors

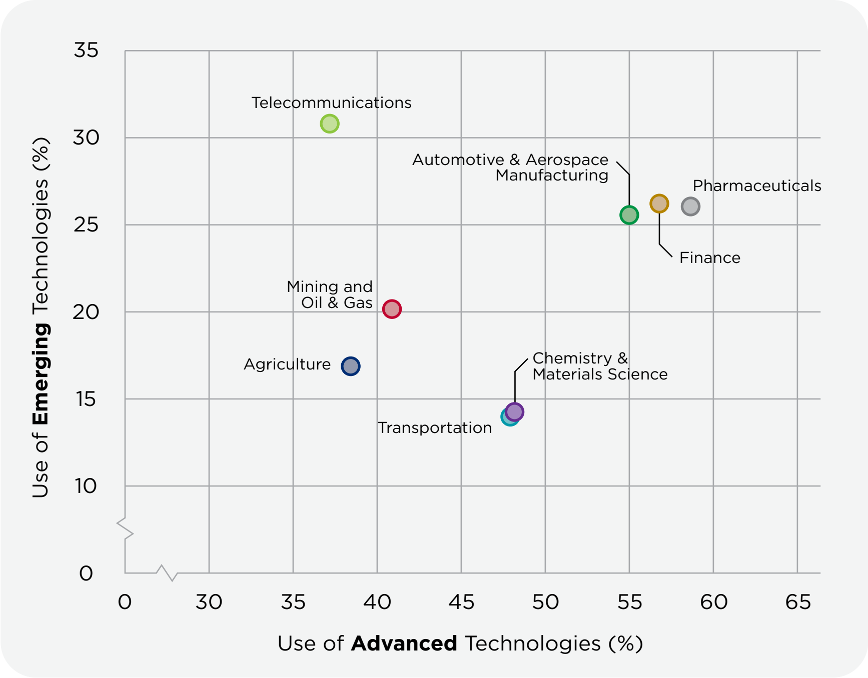
The adoption of quantum technologies in a particular sector or industry depends on several factors, including the existence of practical applications; the potential for improvement over existing classical technology; the availability and maturity of the relevant quantum technology; and the capacity of the sector to invest time, money, and resources into the adoption of quantum technology. Thus, it can be difficult to estimate the likelihood and timing of adoption in different sectors. Some sectors that are expected to be early adopters (i.e., in terms of investments, attention, and R&D) may not have promising applications for years or even decades, while others for which quantum technologies are currently available — or will be available in the near term — are investing fewer resources in them.

However, there is general consensus in the literature that the pharmaceutical, chemistry and materials science, finance, and transportation (including routing, logistics, and aerospace/automotive manufacturing) sectors are likely to be early adopters and have the greatest potential for high-value applications (Langione *et al.*, 2019b; Biondi *et al.*, 2021; Capgemini, 2022). In addition, the telecommunications, defence, and space sectors are frequently cited as potential early adopters with high-value applications (Doyletech Corporation, 2020; Capgemini, 2022). Other sectors identified as likely adopters of quantum technologies include natural resources extraction, healthcare, and energy. In addition, quantum technologies are expected to be continually integrated in fundamental scientific research, in areas such as physics, chemistry, and climate science, among others. A survey of quantum stakeholders in academia, industry, and government identified defence, telecommunications, finance, and natural resources as the highest-priority sectors for quantum technology in Canada, followed by pharmaceuticals, environmental management, and healthcare. However, all seven of these sectors were widely considered to be important among respondents (Doyletech Corporation, 2020).

Use of advanced or emerging technology in a sector may indicate that sector's ability to adopt quantum technologies and its likelihood of doing so

Data from the Statistics Canada *Survey of Innovation and Business Strategy* may provide some insight into which sectors in Canada are most likely to adopt quantum technologies. Figure 2.2 shows the percentage of enterprises in each sector that use *advanced* and *emerging* technologies (see figure caption for an explanation of these categories). As shown, the leaders in the use of emerging and advanced technologies among the selected sectors include the pharmaceutical and finance sectors, and automotive and aerospace manufacturing. Additionally, the telecommunications sector has a relatively high use of emerging technologies.

Figure 2.2 takes the use of any advanced or emerging technology as a proxy indicator of a sector's ability to adopt and use quantum technologies. This is in part because the 2019 version of this survey (upon which this analysis is based) does not include quantum technologies among its list of advanced or emerging technologies (StatCan, 2023a). However, the 2022 version of the survey *does* include questions about the use of quantum technologies (StatCan, 2023b) and should therefore provide a clearer picture of quantum technology adoption among businesses in Canada. The results of the 2022 survey are scheduled to be released in February 2024 (StatCan, 2023c).



Data Source: StatCan (2021)

Figure 2.2 Use of Emerging versus Advanced Technologies in Select Sectors

This figure presents the percentage of enterprises in each sector that use *advanced* and *emerging* technologies. *Advanced technologies* refer to general types of technology, such as material handling, supply chain, or logistics; design or information control; processing or fabrication; security or advanced authentication systems; and business intelligence. By contrast, *emerging technologies* refer to specific technologies, such as nanotechnology, biotechnology, AI, and blockchain. See Appendix A for a full list of relevant North American Industry Classification System (NAICS) codes used to categorize each sector.

2.2.1 Applications for Quantum Technologies in Adopting Sectors

Table 2.2 lists several of the sectors most likely to adopt quantum technologies in Canada and identifies some of the most relevant applications in each sector. These sectors were determined through analyses of their importance to Canada, a general review of the literature, panel expertise, and pre-assessment consultations with the sponsor. It should be noted that this list is not exhaustive and contains only a few of the most notable examples of the potential use cases of quantum technology for each sector. Moreover, it is not prioritized or ranked, but rather presented in alphabetical order. More detailed descriptions of these applications can be found in Appendix B.

It should also be noted that predicting the potential use cases of quantum technologies presents difficulties for at least two reasons. First, there is both a great deal of uncertainty and hype in claims about the capabilities of the technologies. This can make it challenging to distinguish between genuine, realistic applications and exaggerated or inflated claims. Second, predicting the long-term impacts of a disruptive technology is difficult; for instance, nobody in the first half of the 20th century could have foreseen the innumerable ways that transistors or classical computers would impact every aspect of society. Predicting the myriad impacts of quantum technologies will be equally challenging (Ghose, 2020; Simmons, 2022).

Table 2.2 Quantum Technology Applications by Sector

	Computing	Sensing	Communications
Agriculture	• Nitrogen fixation for fertilizer production • Predictive agriculture	• Sensing soil condition for precision agriculture	
Chemistry	• Simulating quantum systems • Materials discovery	• NV centres for NMR spectroscopy	
Defence / Intelligence	• Optimization of military logistics • Military decision-making • Intelligence analysis • Simulating materials for defence applications	• Navigation for submarines • Detecting camouflaged or submerged vehicles and structures • Quantum radar	• Secure communications • Quantum antennas • QRC
Energy	• Energy system optimization • Simulation for sustainable energy materials	• Monitoring infrastructure	
Finance	• Optimization of portfolios • Data analysis • Simulation of markets		• Protecting financial transactions
Healthcare	• Clinical decision-making • Diagnostic assistance • Radiotherapy optimization	• OPM MEG • NV centres for magnetic microscopy and NMR spectroscopy • Detection of magnetic nanoparticles	• Protecting and transmitting health data

	Computing	Sensing	Communications
Manufacturing	• Simulation for product engineering, design, and materials discovery • Optimization of supply chains, routing and logistics, production processes, and production scheduling • Design and manufacture of quantum technologies		
Mining / Oil & Gas	• Optimizing mining operations • Increasing automation	• Detection of underground deposits • Analyzing mineral samples • Monitoring infrastructure	
Pharmaceuticals	• Drug discovery • Simulating the effect of compounds on biological targets	• NV centres for NMR spectroscopy	
Scientific Research	• Simulating particle physics • Analyzing supercollider data • Solving inversion problems	• Testing theories in fundamental physics • Earth observation for climate modelling	
Space	• Mission optimization • Diagnostics and fault management	• Detecting space debris	• Secure Earth-to-space communications
Tele-communications	• Optimizing placement of telecom infrastructure • Wireless traffic routing	• Optical clocks for network synchronization	• QKD and QRC
Transportation and Logistics	• Optimizing transportation logistics and routing • Battery development	• Navigation	• Protecting vehicle control units

2.3 Economic Impacts of Quantum Technologies

The development and commercialization of quantum technologies present significant economic opportunities for both Canada's quantum industry and the Canadian economy more broadly. Doyletech (2020) estimates a 4% share of the global quantum market for Canada, which is described as keeping with the country's "traditional share of technology-based innovations." By contrast, Australia's Commonwealth Scientific and Industrial Research Organisation predicts a 5% market share for Australia (CSIRO, 2022), and Quantum Delta NL, the Netherlands' national program for quantum technologies, has predicted a 5% to 10% market share for that country (QDNL, 2020). The United States and China are predicted to capture the largest global market share for quantum technologies, accounting for roughly three-quarters (~75%) of the overall market (QDNL, 2020).

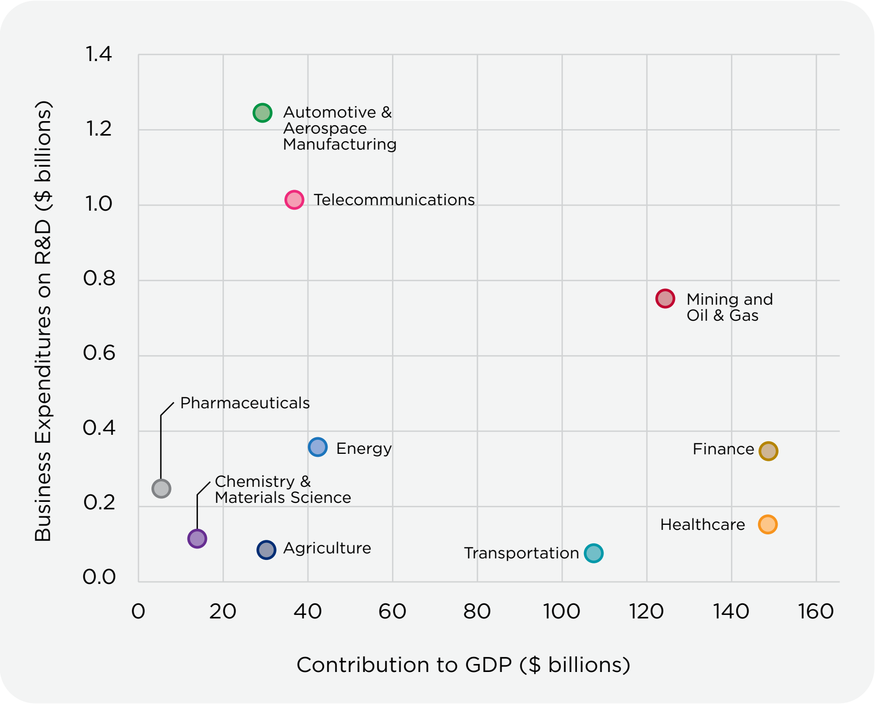
The economic impacts of quantum technologies in Canada are potentially very large

Modelling by Doyletech (2020) — which was commissioned by the NRC and cited in Canada's NQS — projects that the total economic impact of quantum technologies in Canada (including indirect and induced effects) could be $138.9 billion by 2045. This would represent roughly 2.7% to 3.3% of the total Canadian economy in 2045, and result in over $42.3 billion in tax revenues. To put these numbers in perspective, Canada's aerospace sector generated about $28 billion in economic activity in 2016, representing about 1.3% of the total economy (Doyletech Corporation, 2020). Importantly, however, in the panel's view, these (and similar) estimates are highly speculative and should be treated with caution given the difficulty of predicting the economic impacts of technologies that are still years (or even decades) away from maturity and for which few practical applications exist (recall Section 2.1.4). Regardless, quantum technologies may present a significant return on investment for Canada. For example, Quantum Delta NL predicts a roughly eight-fold return on quantum technologies for the Dutch economy over the medium term (QDNL, 2020).

The economic impacts of quantum technologies will likely be concentrated in specific sectors

Figure 2.3 provides some insight into the relative importance of quantum technologies for several economic sectors in Canada, based on each sector's contribution to overall GDP and its capacity to adopt new technologies (measured by business enterprise expenditure on R&D, or BERD). As the figure demonstrates, several of the sectors most frequently cited as early adopters, with high-value quantum potential, make relatively small contributions to Canada's overall GDP (e.g., pharmaceuticals, chemistry), with the exception of the finance sector.

However, there may be niching opportunities for Canada in terms of accelerating the adoption of quantum technologies in sectors with smaller market segments, which other countries are overlooking but which are nevertheless economically important to Canada (e.g., natural resources, healthcare). Similarly, there may be opportunities for Canada to focus on the adoption of quantum technologies in sectors with larger investment in R&D and a history of early adoption of emerging technologies (i.e., automotive and aerospace manufacturing). For example, Canada's recent investments in battery manufacturing for electric vehicles may benefit from the application of quantum computing and sensing technologies.



Data Source: StatCan (2022a, 2022b, 2022c)

Figure 2.3 BERD versus Contribution to GDP for Select Sectors

The x-axis of this figure shows the contribution of each sector to Canada's overall GDP, while the y-axis shows the level of BERD. Sectors are categorized by NAICS codes; a full list of relevant NAICS codes is presented in Appendix A. Importantly, there are some qualifications for this figure related to interdependencies among sectors. For example, the agricultural sector could potentially benefit from quantum simulation that could lead to better catalysts for nitrogen fixation and more sustainably produced fertilizers (Appendix B). However, the development and manufacturing of those catalysts will fall to the chemical manufacturing sector.

A similar analysis of Canadian sectors most likely to be impacted by quantum technologies found that the information and communications sector is likely to account for the largest portion of the quantum market in Canada, followed by the defence, environmental, and pharmaceutical sectors (Table 2.3).

Table 2.3 Select Market Share and Contribution to GDP by Sector, Ranked by % of National Quantum Market

Sector	% of National Quantum Market, Average 2020-2040	% of GDP (2019)
Information and communications	9.17	4.27
Defence services	7.75	0.63
Environmental and clean technology	5.39	3.36
Natural resources	3.79	7.49
Pharmaceuticals	3.69	0.31
Healthcare	2.50	6.31
Finance and insurance	2.40	6.66
TOTAL	**35.81**	**29.04**

Adapted from Doyletech Corporation (2020)

Estimates for each sector are based on Doyletech's analysis. Totals do not sum due to rounding.

Most analyses of the economic value of quantum technologies focus on technology developers, not adopters

The potential total market size for quantum technologies has been assessed by several different sources. However, these estimates almost exclusively focus on the market size for *suppliers* of quantum technology (i.e., developers of quantum computers, sensors, and communications technology) and not on the economic benefits for the adopters or end-users of these technologies. In addition, all available estimates of the economic benefits for adopters of quantum technologies focus entirely on quantum computing, with no estimates of the value created by the adoption of quantum sensors or communications.

Table 2.4 lists the predicted economic value of adopting quantum computing (at technological maturity) for specific sectors and applications, categorized as *high*, *medium*, or *low*. Note that the sectors are categorized differently than those listed in Table 2.2, and not all sectors listed in Table 2.2 are represented in Table 2.4, since estimates of the economic value of adoption do not exist for all sectors or applications.

Table 2.4 Value of Quantum Computing Adoption for Select Sectors and Applications (US$ billions)

Sector	Value (low, medium, high)	Applications and Estimates
Finance	HIGH ($50–355)	Portfolio optimization: $20–50‡ $50–300* Risk management: $10–20‡ Market simulation: $20–35‡
Transportation/ Logistics	HIGH ($50–100)	Vehicle routing/network optimization: $50–100‡
Aerospace	HIGH ($40–90)	Flight route optimization: $20–50‡ Computational fluid dynamics: $10–20‡ Materials: $10–20‡
Pharmaceuticals	HIGH ($25–130)	Drug discovery and development: $40–80‡ $15–75† Protein therapeutics: $10–50*
Chemistry	MEDIUM ($21–90)	Catalyst and enzyme design: $20–50‡ $1–40* Chemical production: $20–40†
Manufacturing	MEDIUM ($20–30)	Materials design: $20–30‡
Energy	LOW ($10–30)	Solar conversion: $10–30‡
Automotive	LOW ($10–35)	Automated vehicles/AI: $0–10‡ Automotive, general: $10–25†
Telecommunications	LOW ($1–20)	Network optimization: $1–20*

Sources: QDNL (2020); Biondi *et al.* (2021); Bobier *et al.* (2021)

* QDNL (2020)

† Biondi *et al.* (2021)

‡ Bobier *et al.* (2021)

3

Quantum Technology Landscape

Chapter Findings

- Canadian quantum research is abundant, with a high rate of both international and industry collaboration, but other countries have begun to catch up and surpass Canada in research output.
- Canada has the second-most quantum technology firms after the United States, but inventors in Canada are applying for intellectual property protection at lower rates.
- Quantum technology firms in Canada are clustered around several hubs of academic and industry activity, with Atlantic Canada and the territories being largely absent.
- Canada has a variety of supply-side programs to support the development of quantum technologies but has very little in the way of demand-side programs.
- The quantum technology value chain is complicated and international, with several highly precarious links.

Early investments and talent development in quantum-based research have given Canada a strong foundation as it experiences the second quantum revolution; however, given its relatively small population and research budget, there is a risk of losing early domestic advantage to China, the United States, and members of the European Union (Dunlop, 2019; ISED, 2022d). In a report on the development of a national quantum strategy, the evolution of the domestic quantum ecosystem is described as the product of a "relatively neutral Canadian public policy environment," leadership and philanthropy from private investment, successful individual institutions and investigators, and the ability of start-ups to develop their own markets (Dunlop, 2019). As a result, Canada's nascent quantum ecosystem has grown into a small, yet interdisciplinary network made up of industry organizations, research centres, and business accelerators and incubators (Dunlop, 2019).

Canada's quantum technology value chain strongly depends on international partnerships. This, however, is not unique to Canada; several of the necessary materials and components can only be obtained from a handful of foreign suppliers. This chapter will highlight some international dependencies and identify areas of the value chain where Canada may be able to emerge as a global leader.

3.1 Quantum Activity in Canada

Canada's quantum landscape is composed of a range of organizations and institutions that include universities, start-ups, internationally competitive companies, and industry networks and consortia. While Canada has an active and vibrant research and start-up ecosystem, increasing international competition is beginning to challenge its global position. Likewise, Canadian companies are lagging in metrics related to intellectual property (IP) protection; these could be indicators of future challenges related to commercialization and technology adoption. There may be other issues related to technology adoption stemming from Canada's localized hubs of expertise, which largely exclude the Atlantic provinces and the territories. However, Canadian organizations have a wide-reaching international network of partnerships and collaborations, which could help them in a variety of ways, from attracting talent to connecting companies with larger future markets.

3.1.1 Research Activity

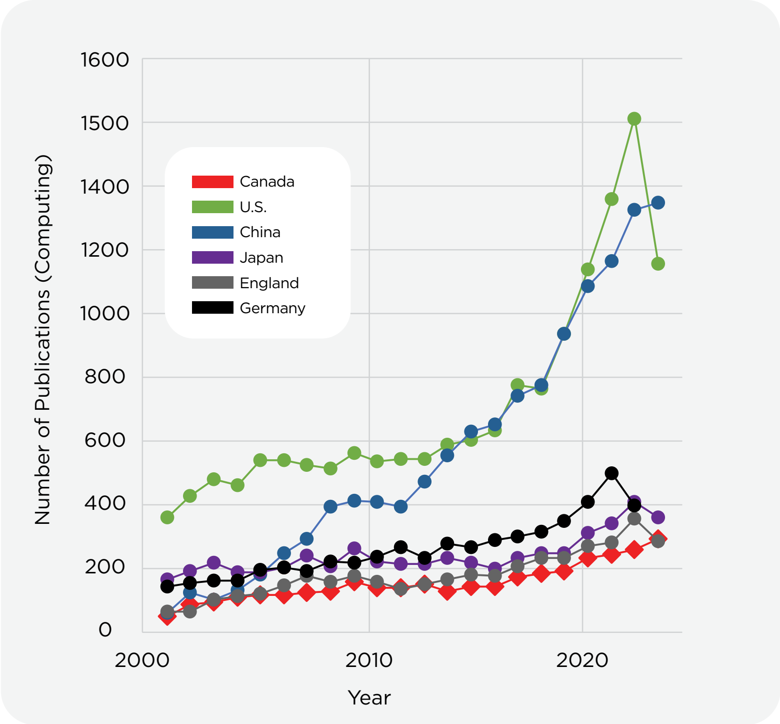
Quantum technologies have been slowly developing for decades and are now beginning to emerge as value-generating products and services. However, there are significant hurdles to overcome, many in the realm of fundamental research.

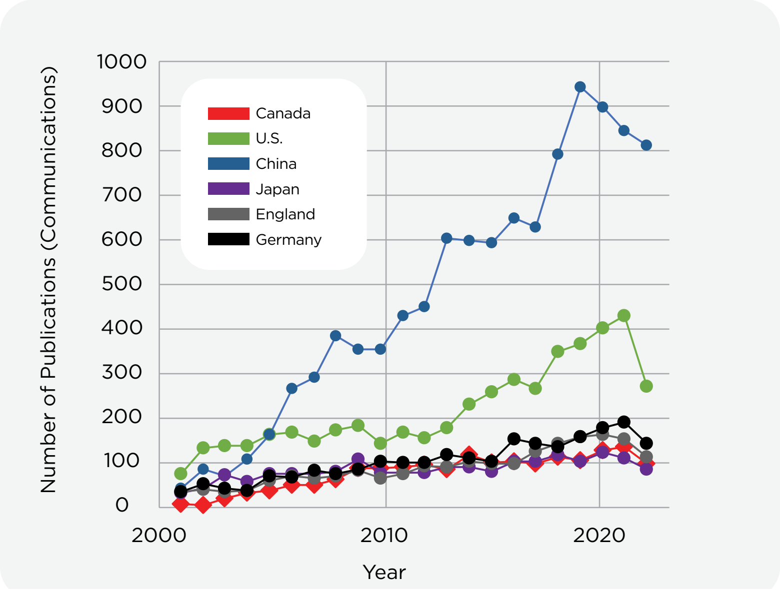
Canada risks being overshadowed by quantum research programs in other countries

Canada is often described as a world leader in quantum research; however, this is not necessarily reflected in the number of quantum-based publications and conference proceedings produced between 2001 and 2022.[5] Figure 3.1 shows the number of publications in this period for several major countries contributing to quantum research, divided into quantum computing, communications, and sensing, respectively. Canada generally ranks in the bottom half of total number of publications for each of these areas, surpassed by China, Germany, Japan, England,[6] and the United States in most cases. Compared to other leading countries, Canada showed consistent if modest growth in total number of publications between 2001 and 2022, while other countries, such as China, Germany, and the United States, experienced far more rapid growth (apart from 2020 to 2022, which generally saw decreased research output).

5 This analysis was done using the Web of Science Core Collection citation index and follows the method and keywords described in Parker *et al.* (2022), which are expanded upon in Appendix C.

6 Web of Science affiliations differentiate England from Wales, Scotland, and Northern Ireland.


1600
1500
1400
1200
1000
800
600
400
200
0
Canada
U.S.
China
Japan
England
Germany
Number of Publications (Computing)
2000
2010
2020
Year


1000
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Number of Publications (Communications)
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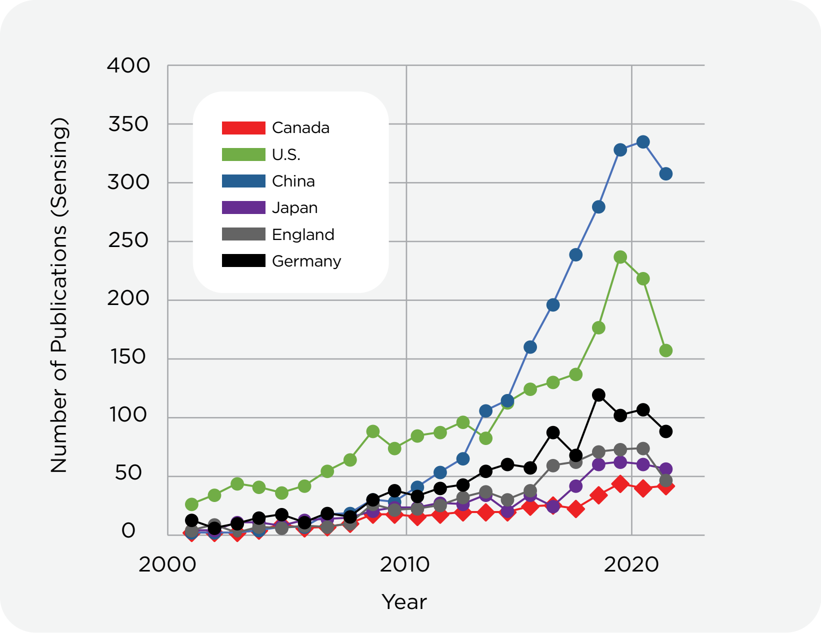


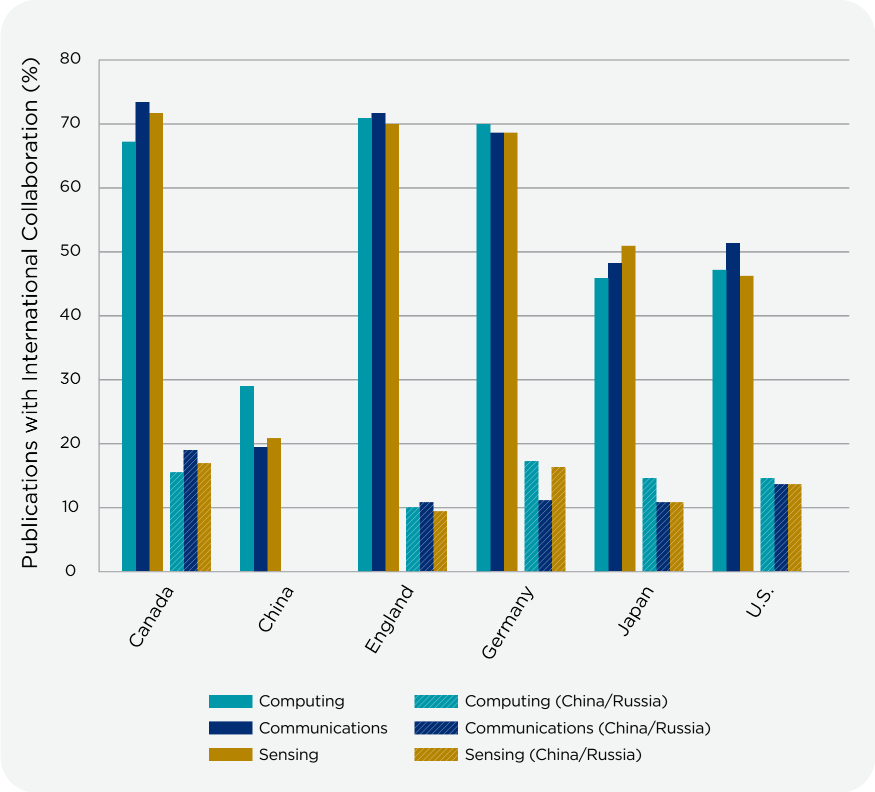
Data Source: Clarivate (n.d.)

Figure 3.1 Quantum Publications and Conference Proceedings Published Between 2001-2022

Canada lags other countries in quantum communications and sensing research, showing more growth in quantum computing research. Data collected from Web of Science analysis (Appendix C).

Researchers in Canada co-authored a significant proportion of publications in quantum communications until 2018, generally staying within the top five countries. After 2018, their contributions to the most-cited communications research dropped below that of several European countries. Compared to the other research areas, quantum sensing is highly variable in terms of which countries produce highly cited publications. China, Germany, and the United States have consistently been some of the largest contributors, but the relatively low number of yearly publications related to quantum sensing (generally around 10% of all quantum-related research output) means small changes in the absolute number of publications can significantly influence a country's rankings. Interestingly, while academic research output in the sensing space is low, patent activity related to quantum sensors is high (Aboy *et al.*, 2022).

In terms of academic publications on quantum, Canada has one of the higher rates of international collaboration, comparable to that of some E.U. member countries. Figure 3.2 shows the rate of international collaboration — defined by publications and conference proceedings — that included at least one international co-author. Additionally, Canada has one of the highest rates of collaboration with China and Russia, particularly in communications and sensing. These data may reflect Canada's relatively small size and modest research budgets compared to countries such as China and the United States, as well as the sometimes prohibitively expensive equipment required for some projects.



Data Source: Clarivate (n.d.)

Figure 3.2 Quantum Publications and Conference Proceedings with International Co-Authors Between 2011-2022

The second set of bars shows collaboration with co-authors affiliated with institutions in China and/or Russia.

There are a variety of benefits associated with active international collaboration, such as shared research costs, increased access to expertise, more opportunities for Canada-based students to train abroad, attracting international students to Canada, and potentially strengthening Canadian supply chains. Table 3.1 ranks the countries with which researchers in Canada collaborate by the number of co-authored research articles. The United States is Canada's most active research collaborator in all areas of quantum, followed by China. Australia, England, and Germany round out the top five, exchanging positions depending on the specific area of research.

Table 3.1 Ranking Canada's Most Active Academic Collaborations on Quantum

Rank	Country	Shared Publications (2001-2022)
1	U.S	1,566
2	China	594
3	Germany	523
4	England	415
5	Australia	326
6	Japan	288
7	France	221
8	Italy	198

Data Source: Clarivate (n.d.)

International collaborations also present challenges, particularly if a project shows market potential. Bringing quantum products to market or obtaining IP protection can be complicated when there are international stakeholders (INDU, 2022b). Furthermore, CSIS has warned researchers and businesses in Canada that building international collaborations may pose intelligence and security risks, or involve economic practices that may disadvantage Canada-based collaborators (for example, China does not have the same laws as Canada regarding IP and equity ownership, which may lead to trade agreements that may disadvantage IP holders in Canada). CSIS has suggested that collaborating with countries with less transparent government practices, such as China and Russia, can be risky and should be approached with care (CSIS, 2018).

In 2023, the Government of Canada announced it will no longer fund grant applications if any researcher on the project is affiliated with a university, research institute, or laboratory with connections to military, national defence, or state security organizations that pose risks to national security, making specific reference to Chinese institutions (Fife & Chase, 2023). This announcement noted, however, that universities were under provincial/territorial jurisdiction and encouraged provinces and territories to adopt similar policies.

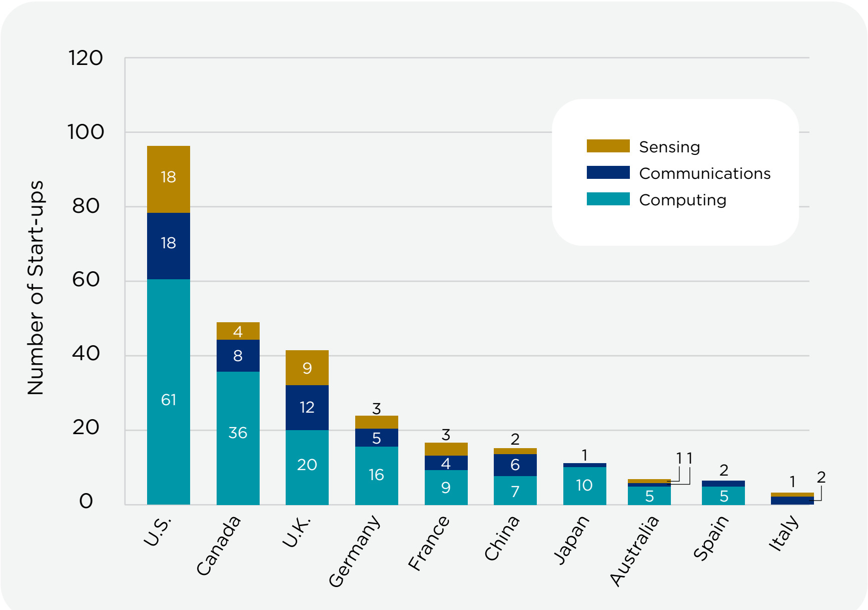
The distribution of Canadian publications points to hubs of expertise in British Columbia, Alberta, Ontario, and Quebec

Canadian research institutions are distributed over a large geographic area and, while there is no single centre of innovation, hubs of quantum expertise have developed in several locations across the country (see Section 3.1.3 for further discussion on hubs of expertise). These hubs are marked by a large number of SMEs, companies that support start-ups, research institutes, and industry networks, as well as publication output. Of the 4,669 quantum-based publications in Canada between 2011 and 2020, 3,031 were attributed to authors in Ontario, 759 in Quebec, 589 in British Columbia, and 455 in Alberta.

3.1.2 Market Activity

Canada has the second highest number of quantum SMEs globally

Canada is home to a large number of quantum-based SMEs. An analysis of the number of quantum-based start-ups around the world found that Canada ranked second globally, behind only the United States (Seskir *et al.*, 2022) (Figure 3.3). The same report showed that Canada's quantum industry is made up exclusively of SMEs and is heavily focused on computing (second-most globally). Although most companies are early-stage start-ups, several of them, including D-Wave and Xanadu, are competitive on a global scale; they do, however, employ far fewer than 500 people and are therefore still considered SMEs. England ranks third in total number of quantum start-ups but surpasses Canada in the number of communications- and sensor-based companies (Seskir *et al.*, 2022). Noticeably lacking are companies based in China, which may be partially due to the study's exclusive use of data available in English.



Data Sources: GACG (2021a); Seskir *et al.* (2022)

Figure 3.3 Start-up Companies by Technology and Country

Computing companies are the most common type of quantum start-up among nearly all countries surveyed

According to Seskir *et al.* (2022), most countries have a larger number of quantum computing start-ups than quantum communications or sensing start-ups. This may be partially due to data collection criteria, which only included companies that were started as quantum technology enterprises and not those that pivoted to exploring quantum technologies. These criteria excluded established companies (e.g., IBM, Google, Microsoft) that set out to develop their own quantum technologies. This may account for the low number of companies focusing on sensors, which are generally considered to be closer to market-readiness and, in some cases, have more straightforward applications for adopting industries, making it a less speculative R&D investment for established companies that wish to develop their own technologies (Seskir *et al.*, 2022).

Canadian entities own relatively few patents compared to those in other countries

Another metric for assessing Canada's engagement in the quantum technology market is IP protection. Table 3.2 shows the share of quantum patents held by companies globally by headquarters location. These data illustrate that, while it does not have many start-ups, China has amassed a large portfolio of IP, perhaps suggesting its companies are especially active. Reciprocally, Canadian entities have far fewer patents, which could be interpreted as a weakness in their quantum strategy. The panel notes that, while patenting may have some utility as an indicator of innovation, IP practices can vary significantly across technologies. Quantum and other disruptive technologies may be overwhelmingly protected through trade secrets. Therefore, care should be taken in drawing conclusions from the following patent data.

Table 3.2 Share of Quantum-Related Patents by Headquarters Location, 2000–2021

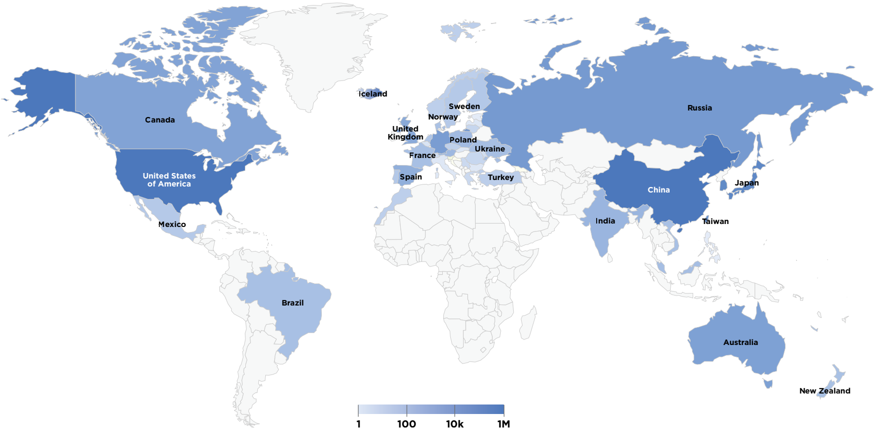
Jurisdiction	Total (%)	Computing (%)	Communications (%)	Sensing (%)
Canada	0.8	0.6	1.6	0.0
China	53.8	54.1	46.2	59.7
E.U.	11.2	11.5	10	14.8
Japan	15.2	15.4	18.4	14.8
Russia	0.6	0.6	0.6	0
U.K.	1.2	1.0	3.4	0.0
U.S.	10	9.6	6.5	4.5

Data Source: Masiowski *et al.* (2022)

Notably, only 50% of patent applications disclosed company headquarter locations. Therefore, this table only represents half of all patent filings.

China and the U.S. issue the most quantum-based patents globally

While the data in Table 3.2 suggest China is exceeding all other countries in patent filings, it is important to note that not all patents are filed in the same markets or offices. Another quantum technology patent landscape study found that China and the United States issued the most patents between 2001 and 2022, suggesting that these are expected to be highly active markets for quantum technologies (Aboy *et al.*, 2022) (Figure 3.4).



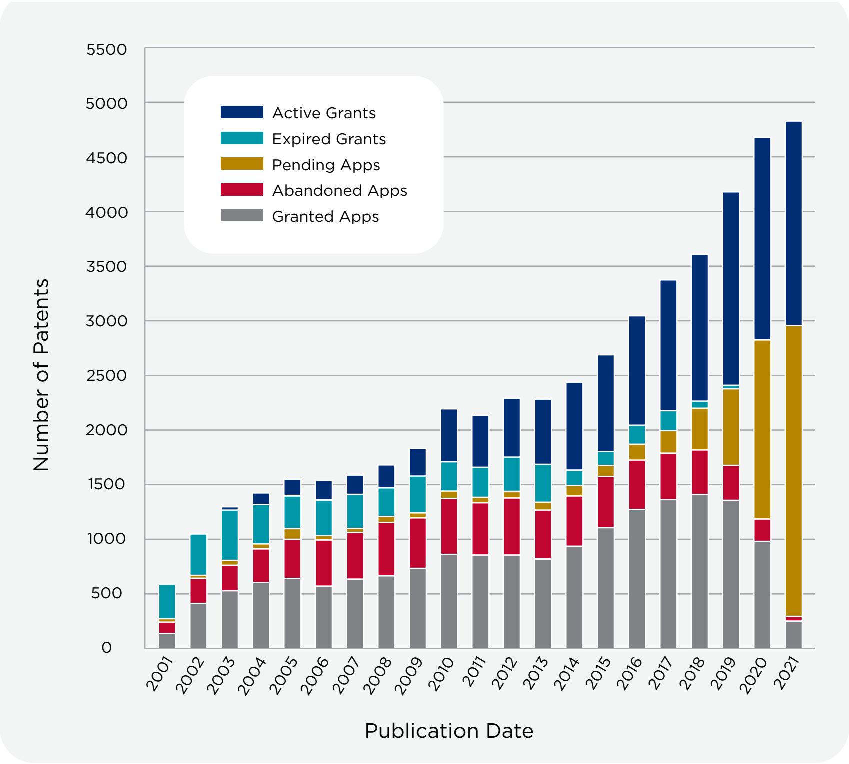
Source: Aboy *et al.* (2022)

Figure 3.4 Heatmap of Countries Issuing Quantum Technology Patents

Top patenting countries of issuance for quantum technology patents (Search ID: S2) by Mateo Aboy, Timo Minssen, and Mauritz Kop with permission from Springer Nature under license CCA BY 4.0.

Limiting the scope of patents to those granted by the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) between 2001 and 2022[7] (a total of 20,583 patents), the number of quantum-related patents have increased significantly since 2001 (Aboy *et al.*, 2022) (Figure 3.5). The most growth occurred (i) between 2001 and 2003 and (ii) since 2014. It is estimated that the USPTO and EPO now jointly grant approximately 2,000 patents related to quantum technologies per year, with nearly 50% of all such patents (10,318) granted since 2015.

7 The search criteria isolated patents that included quantum-related keywords in the title, abstract, or claim. See Appendix D for details.



Source: Aboy *et al.* (2022)

Figure 3.5 Patenting Activity for Quantum Technologies, 2001-2021 (USPTO and EPO)

"Annual patenting activity for quantum technologies at the USPTO and EPO (Search ID: S2) and legal status by publication date of the patent document" by Mateo Aboy, Timo Minssen, and Mauritz Kop with permission from Springer Nature under license CCA BY 4.0.

The analysis by Aboy *et al.* (2022) found that, between 2001 and 2022, the majority of patents were related to devices, followed by nanostructures and optics. Other technologies constituted far fewer patents and are summarized in Table 3.3. Notably, the study found that patents related to "quantum circuits" were the most prevalent between 2001 and 2022. Between 2001 and 2013, communications-related claims constituted the second-highest number of patents. However, after 2013, claims related to quantum computing overtook communications-based claims. Aboy *et al.* (2022) also note that patents with claim limitations directed to "algorithms" were a minority, though even these have increased since 2016.

Table 3.3 Patenting Activity by Technology Category, 2001-2022 (USPTO and EPO)

Category*	Topic	Patent Applications	Patents Awarded
Sensing	Devices	14,243	8,965
	Nanostructures/ optics	4,917	3,282
Computing	Information processing	3,331	2,057
	Computing	3,042	1,603
Communications	Cryptography	1,219	736
	Communications	1,057	632

Data Source: Aboy *et al.* (2022)

*The category divisions are approximate; patents related to a given topic may be applicable to one or more categories and are further described in Appendix D.

Aboy *et al.* (2022) also identified the most prevalent patent assignees over the last 20 years (note that it is common for the inventor to assign any IP developed in the course of their work to their employer). Appendix D shows a summary of some of the notable assignees, including the most active Canadian entities, of which only three (D-Wave, 1QBit, and Quantum Valley Investments) reach the top 50. The study points out that the quantum IP landscape is distributed among a wider range of entities than for classical computing, semiconductors, and telecommunications.

3.1.3 Hubs of Expertise and Quantum Technology Networks

Quantum expertise is unevenly distributed across Canada

Section 3.1.1 showed that quantum-based research originates in several hubs across Canada; British Columbia, Alberta, Ontario, and Quebec have all developed thriving quantum technology ecosystems, and these clusters are somewhat differentiated by speciality. However, this also means that certain regions are not as well represented. For example, Atlantic Canada and the territories are largely absent from the *National Quantum Strategy* (NQS), specifically the Regional Development section of the Commercialization pillar (see ISED, 2023d). The ramifications of an uneven distribution of quantum expertise are discussed in Chapter 4.

National and regional quantum technology research hubs in Canada attempt to facilitate collaboration among researchers, industry partners, and government stakeholders to advance the development and commercialization of quantum technologies. Ideally, these hubs and networks can help develop a talent pipeline that connects students to industry and supports Canada's innovation ecosystem. Some of the programs discussed below are geographically centred hubs, while others seek to connect academic, industrial, and government entities across the country.

British Columbia has a highly collaborative quantum community, with universities conducting research across various fields, such as quantum computing, communications, and materials (S. Simmons, personal communication, 2023). The Stewart Blusson Quantum Matter Institute at the University of British Columbia (UBC, n.d.) and Simon Fraser University's 4D Labs (SFU, n.d.) provide testing, fabrication, and prototyping facilities for researchers and companies developing quantum materials, circuits, and devices. Quantum BC, a joint initiative led by three leading research universities, "aims to stimulate and enrich collaborative efforts across research, training and innovation in quantum computing" (Quantum BC, 2022). Through the NSERC CREATE Quantum Computing program, Quantum BC offers a unique training experience for graduate students in quantum computing hardware and software, in part via internships with industry partners (Quantum BC, n.d.). British Columbia also has a growing ecosystem of quantum technology companies and start-ups. Nine quantum companies collectively employ more than 500 employees, receive more than $270 million in funding and hold more than 404 patents (Mantha & Turner, 2023). Notable companies include D-Wave, 1QBit, Good Chemistry, and Photonic Inc. Quantum Algorithms Institute (QAI) connects academia to industry, and supports the growth of the province's quantum computing ecosystem (Wong, 2021). QAI supports practical initiatives to increase quantum awareness, grow the quantum workforce, and educate new customers about quantum solutions to solve business challenges.

Alberta has a 20-year history in quantum research, development, and commercialization, with major quantum advances and investments totalling over $30 million (CFI, 2023). This is enhanced by synergistic areas of strength, such as nanotechnology and AI. The University of Alberta, University of Calgary, and University of Lethbridge have collaborated since 2015 via Quantum Alberta, a consortium of academic and industry experts who joined together to elevate quantum science and technology R&D and commercialization in Alberta (Quantum Alberta, 2022). Spin-off companies, such as Quantized Technologies Inc., Quantum Silicon Inc., and Zero Point Cryogenics, are part of a nascent, growing quantum start-up culture. In 2022, Quantum City — a partnership among the University of Calgary, the Government of Alberta, and leading technology company Mphasis — was established with over $100 million in private and public investments (UofC, 2022). Quantum City is a global quantum knowledge translation hub, bringing together researchers, quantum companies, and early adopters of quantum technologies and services. It is investing in 15 new University of Calgary quantum faculty positions, as well as training and upskilling programs (e.g., master's in quantum computing, NSERC CREATE in Innovators for Quantum Computing Deployment), in collaboration with the Université de Sherbrooke, a quantum fabrication and characterization facility (qLab), and an incubation and ideas collision hub (qHub) (B.C. Sanders, personal communication, 2023).

In **Ontario**, an ecosystem consisting of Waterloo and the Quantum Valley Hub was established in 2001. It brings together more than a dozen organizations and start-ups working in fundamental physics, experimental implementation, device engineering, and venture capital (TQT, n.d.-a, n.d.-b), including the Perimeter Institute, a non-profit organization focused on foundational physics; the Institute for Quantum Computing, which aims to develop quantum information science and technology; the Quantum-Nano Fabrication and Characterization Facility, which specializes in building quantum devices; a Canada First Research Excellence Fund project with a focus on quantum health; the Quantum Valley Ideas Lab; and Quantum Valley Investments, a $100 million venture capital fund (R. Laflamme, personal communication, 2023). Some of the start-ups include ISARA Corporation, High Q Technologies, Single Quantum, Universal Quantum Devices, Aegis Quantum, and Quantum Benchmark. Quantum Valley was built as a public-private partnership (PPP) and has benefited from ongoing, strong support from the governments of Canada and Ontario, philanthropy (most significantly from Mike and Ophelia Lazaridis and Douglas Fregin), and the University of Waterloo. More than $1 billion has been invested to date. The ecosystem takes advantage of Waterloo's strong innovation base and entrepreneurial culture, existing talent, unique R&D infrastructure, and strong network of collaborators, forming a community with a shared vision of a quantum future.

In **Quebec**, the Innovation Zone in Quantum Science and Technological Applications is formed around the Université de Sherbrooke and represents investments of over $435 million in the region, of which $131 million is public funding (C. Sarra-Bournet, personal communication, 2023). Companies such as 1QBit, Bell, IBM, PASQAL, and Eidos-Sherbrooke have also committed to investments of $270 million over five years. Of note, the Quebec-IBM Discovery Accelerator program is involved with the installation of a 127-qubit IBM quantum computer in collaboration with Plateforme d'Innovation Numérique et Quantique ($PINQ^2$) at its IBM Bromont facility ($PINQ^2$, 2023). Sherbrooke is also the home of Canadian university spin-offs such as Nord Quantique, SBQuantum, and Qubic Technologies. The R&D infrastructure capabilities of the hub are provided by the Integrated Innovation Chain (IIC), led by Institut quantique (IQ), the

Interdisciplinary Institute for Technological Innovation (3IT), and the MiQro Innovation Collaborative Centre (C2MI), which acts as a bridge between university research and the development of new products transferred to industry (Quebec Quantique, n.d.; Université de Sherbrooke, n.d.). Since 2010, the IIC has benefited from more than $1 billion in investments, with more than 60% coming from industrial partners. This ecosystem is part of a semiconductors corridor that was recently part of a memorandum of understanding (MOU) between the United States and Canada related to the U.S. *CHIPS and Science Act* (Platt, 2023) (Box 5.5).

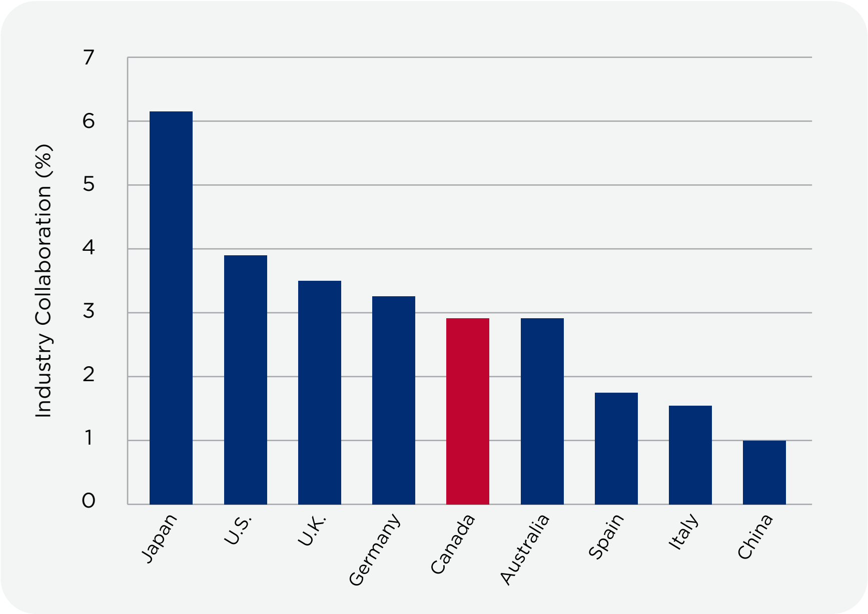
There is a lack of data related to technology transfer metrics for quantum technologies

Technology transfer is a crucial step in converting academic research into marketable technologies, but best practices are hard to identify and implement for several reasons. Technology transfer can happen in several ways, including but not limited to the sale or licensing of IP to industry partners, the creation of companies by researchers at academic institutions, and the transfer of personnel with applicable and novel skills from academia to industry (House of Commons of Canada, 2017). Of these methods, some metrics are directly related to technology transfer (e.g., IP granted, companies spun out of academic institutions), but other factors, such as the hiring of skilled researchers, can be hard to quantify or are otherwise not tracked consistently. Moreover, while some of these metrics can be tracked, it is not obvious how to value them, especially across different disciplines and technologies.

It is difficult to show conclusively that technology transfer offices (TTOs) have facilitated the development or adoption of technologies, or that the models used in universities are well suited to industry (Baglieri *et al.*, 2018; Belitski *et al.*, 2019; Lee & Jung, 2021). Most post-secondary institutions in Canada employ TTOs to facilitate and track interactions between their researchers and industry partners, but tracking is not mandatory or consistent among universities (Sigurdson *et al.*, 2015).

Taking all topics into account, including quantum, most research-intensive U.S. colleges and universities generally have access to more resources than Canadian universities, and they spend significantly more on research (AUTM, 2022a, 2022b). As a result, their technology transfer metrics (e.g., total licences, gross income from licences, patents issued, start-ups created) are systematically higher than those at Canadian universities. However, Canadian universities appear to create more start-ups per $100 million spent on research (Appendix E). That said, U.S. institutions are more efficient at generating other forms of IP and value — IP acquisition and disclosures per $100 million spent on research, for example. Differences among universities in Canada are also evident, which may be a result of different approaches by TTOs and each institution's policies on IP ownership. It is important, however, to remember that these data include all areas of research, not just quantum technologies (House of Commons of Canada, 2017).

Another metric that can help quantify technology transfer between academia and industry is the percentage of journal articles with at least one industry co-author. Figure 3.6 shows Canada has higher rates of collaboration than Australia, Spain, Italy, and China, but lower rates than those of other comparable countries (UofT, 2023).



Data Source: UofT (2023)

Figure 3.6 Industry Collaboration in Quantum Research, by Country

This kind of collaboration can be more broadly identified among all different institutional sectors as *intersectoral collaboration* (number and rate).[8] Using this definition, one study found that, between 2011 and 2020, the total intersectoral collaboration rate for quantum-based publications was 19% (increasing from 17% between 2011 and 2015 to 22% between 2016 and 2020) (Robitaille *et al.*, 2022). This rate was found to be higher than that of mathematics (3%), chemistry (10%), engineering (11%), and physics (15%), but lower than that of biology (24%), biomedical research (30%), and clinical medicine (40%). It also found that, while post-secondary institutions were the largest contributors to quantum technology research (88%), "other" sectors (mostly composed of not-for-profit organizations)

8 A publication is defined as an *intersectoral collaboration* when authors list addresses from at least two different sectors (e.g., a university researcher may co-author a publication with a researcher from industry or government). The rate is the number of intersectoral collaborations divided by the total number of publications attributed to each entity (Robitaille *et al.*, 2022).

accounted for 22%. This rate can be compared to "other" sectors' activity in other natural sciences and engineering disciplines, where they only contributed to 4% of the overall publications. Robitaille *et al.* (2022) attribute this large difference to research activity at the Perimeter Institute and research supported by CIFAR which produced 678 and 354 publications over this period, respectively. Table 3.4 provides a detailed breakdown of intersectoral collaborations between 2016 and 2020.

Table 3.4 Intersectoral Collaboration Matrix of Canadian Quantum Technology Publications, 2016–2020

Sector 2 / Sector 1	Federal Government	Hospital	Industry	Post-secondary	Provincial/ Territorial Government	Other
Federal Government		0.9%	4.5%	73.6%	0.0%	10.0%
Hospital	5.3%		0.0%	89.5%	5.3%	10.5%
Industry	5.3%	0.0%		38.4%	0.0%	10.6%
Post Secondary	5.3%	0.8%	2.7%		0.2%	18.8%
Provincial/ Territorial Government	5.3%	25.0%	0.0%	100.0%		0.0%
Other	5.3%	0.3%	2.7%	67.9%	0.0%	

Data Source: Robitaille *et al.* (2022)

Canada has a strong roster of companies, private funders, and industry networks that can support quantum technology start-ups

While TTOs often act as facilitators between academia and industry, intermediary companies can also enable the adoption of new technologies (Miller, 2022). These companies can help start-ups get off the ground, connect them to larger markets, and generally help build and mediate connections among organizations in an innovation ecosystem. Some of the services that intermediary companies offer include research and roadmapping, facilitating connections among potential partners, IP management, hands-on testing, talent development, financing opportunities, and commercialization advice.

Beyond academy and university-based research institutions, Canada is home to many technology incubators, accelerators, and industry groups that can help connect SMEs to financial and technical support. However, identifying best practices or the efficacy of these programs is difficult. Table 3.5 lists some notable organizations, many of which have quantum technology streams and are actively seeking early-stage quantum start-ups to partner with or finance.

Table 3.5 Organizations Supporting the Development and Adoption of Quantum Technologies

Organization	Details
Business Development Bank of Canada (BDC)	A federal Crown corporation mandated to help Canadian SMEs with financing, growth, transition capital, venture capital, and advisory services. In 2021, the BDC launched its $200 million Deep Tech Venture Fund focusing on equity investments in early-stage quantum technologies (BDC, 2022).
Canadian Technology Accelerators (CTA)	A collection of programs under the Canadian Trade Commissioner Service (TCS) to help with global business development in 12 technology hubs in North America, Europe, and Asia-Pacific. These TCS programs help with mentorship, introductions to potential investors and clients, and, in some cases, collaborative workspaces. The focus is on international markets (TCS, 2021b).
CIFAR	A registered charitable organization that funds researchers and programs across a range of areas. It provides funding to research fellows, advisors, Global Scholars, research chairs, institutions, and international partners via several programs, including Quantum Information Science and Quantum Materials (CIFAR, 2022a, 2022b). CIFAR is supported by the governments of Canada, Alberta, and Quebec, along with Canadian and international foundations, individuals, corporations, and organizations.
Creative Destruction Lab (CDL)	A not-for-profit organization that offers programs to help seed-stage technology businesses develop financial models and scaling strategies. It has expanded its programs from Toronto to 11 additional cities, including Vancouver, Calgary, Montréal, Halifax, and several foreign cities. As of 2023, the CDL-Quantum stream has worked with 50 quantum technology start-ups (CDL, n.d.).
Cyber Security Innovation Network	An initiative funded by ISED with the goal of supporting industry-academia collaboration in developing Canada's cybersecurity infrastructure (TCS, 2021b). In 2021, the National Cybersecurity Consortium (NCC) (founded in 2020 by Concordia University, Toronto Metropolitan University, University of Calgary, University of New Brunswick, and University of Waterloo) was chosen to lead this initiative (GC, 2022c).

Organization	Details
Mitacs	A non-governmental organization with the goal of improving Canada's technical expertise and innovation ecosystems through training, connecting students to industry partners, and building connections between Canada and foreign partners (Mitacs, 2021). Mitacs has been identified in Canada's NQS as a key component of the Talent pillar and has received $40 million to fund quantum technology programming (NSERC, 2022; ISED, 2023d). It also works with NSERC through its CREATE program.
NSERC CREATE	An annual competition intended to attract, develop, and retain teams of HQP at the level of student and post doctoral fellow. The competition is offered annually, and will fund at least three grants for quantum science research (NSERC, 2023).
PINQ²	A not-for-profit organization with the goal of supporting companies in making digital transitions to new technologies. PINQ² has noteworthy connections to the Quebec-IBM Discovery Accelerator, offering support for companies seeking to integrate quantum computing as a service (QCaaS) into their operations (PINQ², 2023).
Quantum Industry Canada (QIC)	A consortium of Canadian quantum technology companies launched in 2020 with the goal of connecting start-ups and mature companies to international markets, expertise in IP management, and other quantum-interested companies (QIC, 2020). The 31 member companies include developers of technologies for quantum computing, communications, sensing, and QRC.
Quantum-Safe Canada	A not-for-profit group concerned with the responsible and safe adoption of quantum-based technologies, especially related to cryptography and encryption (Quantum-Safe Canada, n.d.). Quantum-Safe Canada sees the U.S. National Institute of Standards and Technology (NIST) process as the "key external organizing factor" for transitioning to quantum-ready computing; it has identified Quantum Encryption and Science Satellite (QEYSSat) and Open Quantum Safe (an open-source software project for developing QRC) as key projects that can help achieve its goals (Quantum-Safe Canada, n.d.).
Quantum Valley Investments (QVI)	A private investment fund in the "Quantum Valley" surrounding the Waterloo region. The focus of this $100 million fund is on quantum information science breakthroughs with commercial potential. The fund offers R&D space and proximity to other Quantum Valley institutions (QVI, 2022).
Venture and other funding providers	There has been significant venture capital invested in Canadian quantum computing companies as of 2022 (e.g., QCR, 2022).

3.1.4 Public Funding

Historically, Canada had well-funded quantum programs but now lags other countries' funding for quantum strategies

As of 2022, Canada and many other countries have either announced or released a national quantum strategy for the development and adoption of quantum technologies. Quantum technology has been an item in several federal budgets in Canada, with large investments allocated for developing and pursuing a domestic NQS. Current public funding for quantum computing in several countries is shown in Table 3.6. As expected, the amount of public funding available in Canada is not as high as it is in countries such as China and the United States, but it is comparable to European countries surveyed. However, several of the countries listed in Table 3.6 are also members of the European Union, which has launched its US$1 billion Quantum Flagship program (Cartlidge, 2018). Canada has some international collaborations, but nothing on the scale of the European Quantum Flagship program.

Table 3.6 Quantum Technology Investments by Countries with High Quantum Research Output

Jurisdiction	Year Announced	Amount (US$ billions)	Details
Australia	2021	Up to 1 (Smith & Coorey, 2023)	Supporting national quantum strategy and other critical technology
Canada	2021	0.3[9]	Supporting the NQS over 7 years (other sources claim US$1B, which may include funding intended for related initiatives) (ISED, 2023d)
China	2017	25.3	Public information is limited
E.U.	2022	1.1	EU's Quantum Flagship, over 10 years (E.C., n.d.)
France	2021	2.2	National strategy, over 5 years
Germany	2021	4.8	Support for a quantum framework, up to 2028
India	2020	1.0	Supporting national quantum strategy, over 5 years
Japan	2020	0.7	
Russia	2020	0.7	
U.K.	2023	4.4	National strategy, over 10 years (previous funding announced in 2018); additional UKRI awards (UKRI, 2023)
U.S.	2018	2.8	National Quantum Initiative Act (spread across 5 hubs)

Source: UofT (2023) unless otherwise noted

9 Based on the Bank of Canada's 2021 annual exchange rate (US$1 = CA$1.2535) (Bank of Canada, n.d.).

Canada's NQS allocates funding according to three pillars: Research, Talent, and Commercialization

Prior to the release of Canada's NQS, the federal government announced it would be providing an additional $360 million toward developing quantum technologies, companies, and talent (FIN, 2021). In 2023, details were shared about how this funding will be allocated (ISED, 2023d). The strategy outlines three major pillars that will each be supported directly by several programs, as well as a variety of related programming. Appendix G summarizes the various funding packages provided through the NQS.

In addition to this three-pillar framework for funding programs, the NQS also emphasizes the need for coordinated governance. It plans to establish several levels of governance (ISED, 2023d):

- a **Quantum Advisory Council**[10] composed of industry (both enabling and adopting companies), academia, not-for-profit organizations, and investment communities (Section 6.3);
- **mission-specific working groups** tasked with developing roadmaps, milestones, and identifying potential investment priorities;
- a **Quantum Committee** supported by the **NQS Secretariat**, which will coordinate with all federal departments that have an interest in quantum technology to ensure there is a unified and connected implementation of the NQS; and
- the **Quantum Research and Development Initiative (QRDI)**, a new $9 million program under the NRC to help academia and industry connect with government-based expertise and infrastructure, in order to accomplish the goals set out in the NQS.

10 It should be noted that the panel's chair, Raymond Laflamme, and peer reviewer, Stephanie Simmons, have been appointed co-chairs of Canada's Quantum Advisory Council, and panel member Shohini Ghose has been appointed as a member of the Council. These appointments occurred several months after they were recruited to the CCA's panel.

Box 3.1 Panel Reflections on the National Quantum Strategy

Overall, the panel is pleased with Canada's NQS as a first step. It does, however, highlight the need for a comprehensive and thoughtful approach to implementation. The panel agrees with the NQS emphasis on key issues in quantum technology, such as materials and infrastructure, but found it lacking in considerations about the adoption and implementation of these technologies by potential users — often a key indicator of market-readiness. Similarly, the strategy minimally addressed ethical, legal, social, or policy issues around the development of quantum technologies. The panel noted a disconnect between the ambitions outlined in the NQS and existing programs, and how roadmapping could help address this issue. It also identified the need for metrics to measure the success of funding and the importance of materials in quantum technology. The panel raised concerns about the spread of funding across the country; while quantum infrastructure and facilities allowing all of Canada to access quantum technologies are crucial, this should not come at the cost of reducing support for innovative hubs. The panel believes addressing these challenges will require cohesion across academia, industry, and government, potentially through the Quantum Committee and NQS Secretariat identified in the strategy.

3.1.5 International Co-operation

Canadian researchers are active collaborators in international research, with almost 70% of their quantum-based publications affiliated with international institutions. Because of Canada's relatively small population size, becoming a major part of the quantum technology industry will require international commercial partnerships (Dunlop, 2019; ISED, 2023d). Specifically, Canada can seek to benefit from international collaborations by embedding itself in international value chains (by producing specialized enabling technologies), participating in developing interoperability standards, hiring or training highly qualified personnel from abroad, as well as continuing to pursue international research collaborations (ISED, 2023d).

Canada has a variety of international collaborations at the government and industry levels

In addition to international relationships among academic researchers, a variety of international collaborations and projects are already underway. Some of these initiatives are being spearheaded by governments, but many private companies are also engaging in international collaborations. The NQS has committed to funding a variety of programs meant to stimulate this sort of international collaboration (ISED, 2023d). NSERC's Alliance grants, for example, have an international stream that supports university researchers in developing connections outside Canada, while the Canadian International Innovation Program (CIIP) operated by the TCS is targeted at Canadian companies. The NQS also outlines several ongoing international projects between the United States and European countries (ISED, 2023d). Some notable international collaborations are listed in Table 3.7.

Table 3.7 Select International Collaborations and Programs Supporting the Development and Adoption of Quantum Technologies

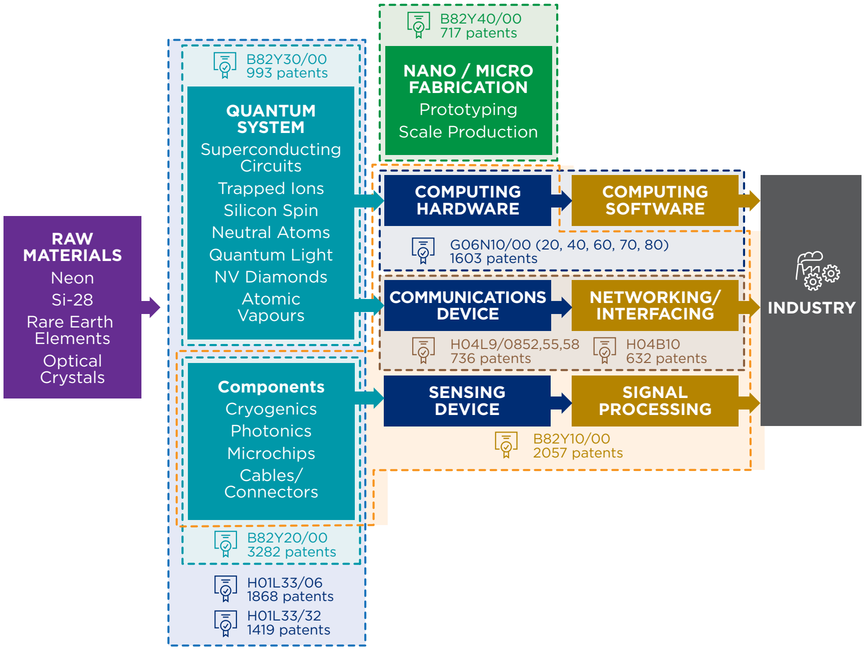
Initiative	Details
Canada-UK Quantum Science Partnership	Announced in 2023, this initiative committed to increasing collaborative research, the training of highly qualified personnel, and the development of robust supply chains for quantum products (ISED, 2022f).
Ericsson Canada, Université de Sherbrooke, and University of Ottawa	Launched in 2023, a new quantum research hub in Montréal focussed on quantum-based algorithms relevant to telecom networks and distributed quantum computing. The program pairs Ericsson researchers with post-doctoral fellows from the Université de Sherbrooke and University of Ottawa (Ericsson, 2023).
France-Canada International Research Network (IRN) on Quantum Science and Technology	A collaborative program between Canadian and French researchers currently involving 16 universities (in Canada, McMaster University, Université de Montréal, Université de Sherbrooke, University of British Columbia, University of Calgary, University of Ottawa, University of Toronto, and University of Waterloo) (CNRS, 2022). The initiative focuses on campus-based research, incorporating young scientists and student exchanges.
Google/Alphabet	Google/Alphabet worked with Anyon Systems on simulations for quantum processors in 2017, and with Kitchener-based Quantum Benchmark in 2018, pairing the latter's error detection software True-Q with Google's open source Cirq framework (Anyon Systems Inc., 2017; Simpson, 2018).
Microsoft	The firm currently offers cloud-accessible quantum computers and a variety of software services developed by Microsoft and its international partners, which include Canadian companies 1QBit, ProteinQure, Xanadu, and Zapata Computing. Azure Quantum also provides cloud access to hardware developed by Quantinuum, IonQ, Quantum Circuits, and Rigetti Computing (Microsoft, 2022). Microsoft is a founding member of B.C.'s Quantum Algorithms Institute (Wong, 2021).
NSERC-UK Research and Innovation (UKRI) Quantum Technologies Competition	Eight projects by researchers in Canada, along with U.K. industry and academic collaborators, shared grants worth £2 million from the United Kingdom and $4.4 million from Canada in 2020 (NSERC, 2020b). Award recipients included quantum projects related to computing, communications, and sensing (NSERC, 2020a).

Initiative	Details
NSERC and National Science Foundation (NSF)	These Canadian and U.S. agencies signed an MOU in 2021, formalizing their intent to further support fundamental research collaborations in several areas, including quantum (NSERC, 2021b).
NSERC and the European Commission (Horizon Europe)	These agencies called for collaborative projects in 2021 focusing on quantum computing and simulation, networking and communications, as well as sensing and metrology, emphasizing the development of strategic partnerships in research, education, and training (NSERC, 2021a).
QEYSSat and ReFQ	QEYSSat is funded by the Canadian Space Agency in collaboration with the University of Waterloo's Institute for Quantum Computing and Honeywell (GC, 2022f). ReFQ is jointly led by Craft Prospect in the United Kingdom and the University of Waterloo. The project seeks to develop technology to help QEYSSat transmit quantum signals between space and ground stations (UKRI, 2020b).
Quebec-IBM Discovery Accelerator	Announced in February 2022, this initiative plans to build a quantum computer (IBM Quantum System One) at the IBM facility in Bromont, Quebec. This facility will be the core of the IBM Quantum Hub at Université de Sherbrooke's Institut quantique. The focus of the program is on computing and material design, using quantum processor and semiconductor expertise and AI-aided modelling (IBM, 2022b).

3.2 The Quantum Value Chain

Most second-generation quantum technologies are in their infancy; this makes any quantitative value chain assessment or analysis of the steps going from raw materials to consumer-ready products difficult. However, outlining the enabling technologies and current state of commercial applications can be useful in identifying challenges, opportunities, and bottlenecks in the path to commercialization. Generally, quantum technologies rely on some sort of *quantum system*, broadly referring to the part of the technology that prepares, manipulates, and measures quantum materials or components (in computing, for example, this would be the set of qubits). Quantum technologies also depend on a variety of classical components (e.g., cryogenics, lasers, semiconductors) that may already be in production in other industries. There is also a need for a variety of products (e.g., software, algorithms, networking, signal processing) that allow consumers to use these technologies.

In a 2022 survey of 47 international quantum computing industry representatives, the top supply chain concerns over the next three years were a lack of key raw materials (21%), manufacturing/assembly equipment (17%), expertise in the design and production of hardware (17%), and expertise in software development (13%) (QED-C, 2022c). Figure 3.7 provides a high-level view of the quantum technology value chain.



Data Sources: Aboy *et al.* (2022); Shaw (2022)

Figure 3.7 The Quantum Value Chain for Computing, Sensing, and Communications, with Number of Associated Granted Patents, 2001-2021

Patent data is presented in terms of USPTO and EPO kind codes (e.g., B82Y10/00).

3.2.1 International Dependencies

Most quantum technologies cannot currently be bought off the shelf, and the list of parts and materials needed to build them could include hundreds of different vendors. Moreover, many of these components may only be available from one or two vendors globally, and specialized equipment could, in some cases, be back-ordered by a year or more (INDU, 2022b). Although quantum computers are some of the most complicated quantum technologies, communications and sensing devices may also experience similar supply chain challenges and international dependencies. Table 3.8 summarizes the findings of Section 3.2 and lists some of the more crucial raw materials and manufactured components that Canadian quantum companies must currently import, linked to their countries of origin.

Table 3.8 International Supply Chain Dependencies Related to Quantum Technologies

Category	Product	Major Suppliers	Precarity	Criticality	Notes
Raw Materials	Neon	Ukraine, China	High	Medium	
	Si-28	Russia	High	Low	
	He-3	Russia, U.S.	Medium	High	Canada has potential as a major supplier
	Sapphire wafers	Russia, Japan	Medium	Medium	Trapped ion applications
	Rb-87	U.S.	High	?	Canada has potential as a major supplier
	Rare Earth materials	China	Varies	Varies	
	Ca-43	U.S.	?	?	Supplied by Oak Ridge National Laboratory
	Barium isotopes	U.S.	?	?	Supplied by Oak Ridge National Laboratory
Manufactured Components	Dilution refrigerators	Finland, U.K., Netherlands	Low	High	One company leads the industry, but others can offer supplies
	Cables/ connectors	Netherlands, Japan	Low	High	
	Lasers	Germany, Japan, U.S., Australia, Canada	Varies	High	
	Semi-conductors / chips	Taiwan, U.S.	High	High	Certain products are currently only available from Taiwan
Manufacturing / Fabrication	Prototyping	NA	Low	High	Canada has a variety of potentially suitable facilities
	At-scale production	China, U.S.	High	Medium	

Data Sources: Giles (2019); Parker *et al.* (2022); INDU (2022b); QED-C (2022c)

Geopolitical events can also affect access to materials and devices (INDU, 2022b). For example, starting in 2022, war in Ukraine significantly reduced the availability of crucial materials such as neon gas and high-purity Silicon-28, while much of the world currently depends on Taiwan for certain types of semiconductors and microcontrollers. Assessing international supply chain dependencies is not trivial. In some cases, the provenance of certain components or materials may not be apparent. For example, electronics, rare Earth magnets, and other raw materials may be sourced from foreign vendors, but where these vendors source the materials may not be known (Parker *et al.*, 2022).

The quantum technology industry's demand for specialized products and materials is small compared to other industries

Supply chain difficulties stem from limited supplier bases and issues with product quality (Parker *et al.*, 2022; INDU, 2022b). In some cases, the quantum technology industry is not currently large enough for suppliers to manufacture more than a few specialized components at a time or may instead make them to order. Similarly, large manufacturers with slim margins may not be able to justify producing such small quantities of specialized equipment. This can add an extra level of scarcity for certain resources, as quantum technologies may not be priority markets for suppliers. For these reasons, larger quantum start-ups have expressed interest in obtaining — or have begun producing for themselves — more of the components required for their technologies (INDU, 2022b). However, this strategy is challenging, as the infrastructure needed to build these specialized devices can be prohibitively expensive.

3.2.2 Raw Materials

Lasers are commonly cited as significant bottlenecks

A wide variety of electronics depend on rare Earth metals many of which are sourced from China. Applications that use photonics technologies (e.g., sensors, communications products) may depend on specialized lasers, which can have different raw material needs than other qubit technologies (Parker *et al.*, 2022). With lasers and optically trapped qubits in particular, the scarcity of materials that allow one to produce specific types of beams and qubits (e.g., Rubidium-87, Calcium-43, Barium isotopes) creates design trade-offs: firms must sometimes choose between less-than-ideal materials or more accessible laser devices versus using a specialized laser system that could make a firm reliant on a new, niche supplier (Parker *et al.*, 2022).

Rubidium atoms have been proposed for use in quantum computing and sensors (Singh *et al.*, 2022), with Canada possibly becoming a new global source (Jaccobsen, 2022). Canadian sources of rare Earth metals are also currently being explored for their usefulness in green technologies (Climenhaga, 2022). Other materials — such as Calcium-43, Barium isotopes, rare Earth magnets, and optical materials — remain difficult to source (Parker *et al.*, 2022).

Neon gas and Silicon-28 supplies are dependent on Russia and Ukraine

Neon gas, a critical component in semiconductor production and sourced largely from Ukraine, became inaccessible following the war that started in 2022 (Alper, 2022). While some countries and larger companies had amassed stockpiles of neon, smaller companies such as quantum start-ups are no longer able to access neon gas. Likewise, Silicon-28 is a relatively abundant isotope of silicon, but isolating and purifying it requires specialized equipment not available to most (Tyson, 2022). Before 2022, Russia was a large source of Silicon-28; while there are efforts to develop scalable techniques of purifying Silicon-28, there are currently no widely available sources (Webb, 2014).

Helium-3 may become a key computing bottleneck; however, Canada has newly discovered sources

Helium-3 is a *primordial nuclide*, meaning it was naturally created before the formation of the Earth (Bania *et al.*, 2002). It is found within the Earth's crust, from where it can be mined, captured, or otherwise released into the atmosphere. While mineable stores of Helium-3 exist, there is a non-replenishing, limited supply of the isotope. Due in part to COVID-19-related supply chain issues and the use of Helium-3 in some medical imaging applications, demand has outpaced production in recent years, causing the price to increase consistently year over year since 2010 (Green *et al.*, 2021).

Canada has the fifth-highest natural abundance of helium, mostly sourced from Saskatchewan. As of 2022, Saskatchewan produced around 1% of the world's supply, but the province announced it intends to raise its output to 10% by 2030, stimulated by new incentives and tax credits (Canada Action, 2021; Nickel, 2022). Newly discovered helium stores in Alberta are also being explored (Shea & Morgan, 2010; Aldrich, 2023).

The high cost of mining Helium-3, along with its scarcity, currently makes it more cost-effective to collect it as a by-product of other processes, namely from nuclear energy and weapons programs (Shea & Morgan, 2010); it can be created from the radioactive decay of tritium, which is a critical component of nuclear warheads. Historically, much of the world's Helium-3 supply has come from these sources. Because it can also be converted into tritium, it is a controlled nuclear substance, according to Canada's *Nuclear Non-Proliferation Import and Export Control Regulations* (SOR/2000-210); this makes it subject to import-export restrictions (GC, 2010).

3.2.3 Manufactured Components

Different quantum technologies may have several overlapping manufacturing and component requirements

At their core, quantum computing, communications, and sensing rely on preparing and measuring quantum states that can be interpreted in ways that allow users to perform calculations, transmit information, or quantify some aspect of the environment (Hoofnagle & Garfinkel, 2021). Computers and other devices can achieve this in a number of different ways, but, in general, each method will require a variety of highly specialized manufactured components working together.

Qubits can be based on several quantum systems, some of which are more relevant, accessible, or near-to-market than others. For instance, most realizations of noisy intermediate-scale quantum (NISQ) computers rely on superconducting qubits and ion traps, though other technologies are also being explored (Dekate *et al.*, 2021) (Section 2.2.1). Similarly, communications technologies and sensor-based devices will have their own prevalent architectures. However, some supply chain requirements are common to many if not all quantum systems. Cryogenic devices, for example, are critical in reducing the kind of signal noise that limits the practical use of certain quantum systems (Green *et al.*, 2021). Likewise, specialized nanofabrication techniques, facilities, and materials are needed to build some of the components that make up computers, sensors, and communications technologies (Laucht *et al.*, 2021). Access to these facilities and components — and the required lab consumables — can be scarce and expensive, in some cases limiting market access to all but the largest companies and governments.

Cryogenics systems are needed in many quantum applications

Second-generation quantum technologies depend on controlling the quantum properties of atomic and subatomic systems. These systems are generally very sensitive to small perturbations from their environment, causing errors and lost information. Once encoded with information, the qubits may decohere before they can be measured or used in a calculation. For some technologies, coherence times can be increased by keeping the system supercooled (Ezratty, 2021). Dilution refrigerators are currently the most practical way of achieving the low temperatures required for keeping these systems stable; however, they are typically large, expensive devices with high energy requirements that need expensive consumables to operate (Green *et al.*, 2021; Hoofnagle & Garfinkel, 2021). However, cooling an entire device to such low temperatures is impractical. As a result, many designs divide layers by their cooling requirements, off-loading less-intensive cooling requirements to more efficient devices (Charbon *et al.*, 2016; Patra *et al.*, 2018). Another critical aspect of these systems involves the cables and wiring that span the different cooling layers (Giles, 2019). These materials are also offered by a limited number of companies globally.

Few Canadian companies offer dilution refrigerators suitable for quantum computing applications

As noted above, dilution refrigerators are highly specialized instruments that can cost hundreds of thousands of dollars. Growth Market Reports projects that the dilution refrigerator market will reach over US$200 million by 2027 (up from US$112.1 million in 2019). Despite the projected increase, dilution refrigeration is a niche market serviced by only a few companies — Oxford Instruments, Bluefors, Lake Shore Cryotronics, Leiden Cryogenics, and Cryomagnetics (Growth Market Reports, 2021). As of 2023, Zero Point Cryogenics and Anyon Systems are the only two companies in Canada advertising dilution refrigeration systems for quantum applications (GACG, 2021a). In 2022, the NRC sponsored a call for Canadian businesses to test and demonstrate new tabletop dilution refrigerators (ISED, 2022c). According to the call, dilution refrigerators are "still very large and complex, basically requiring a whole dedicated laboratory to house them and PhD trained staff to operate" (ISED, 2022c). The call asks for tabletop systems that are easy to operate without specialized knowledge, reach low enough temperatures for quantum technologies, and have enough room to house complex quantum components. Other significant challenges include the energy requirements and consumables needed for the operation of dilution refrigerators, namely Helium-3 and Helium-4.

Taiwan is a global bottleneck for chip-based devices

Some advanced semiconductor chip-based components are only produced at scale in a small number of facilities. Industry representatives from Canadian quantum companies identified Taiwan as a global bottleneck for a range of crucial electronic components not limited to the quantum industry (INDU, 2022b).

Supply chain issues related to the COVID-19 pandemic emphasized the precarity of the global market, which motivated increased spending by a variety of governments, including the United States and members of the European Union (Shankland, 2022). The U.S. *CHIPS and Science Act* committed US$52.7 billion for "semiconductor research, development, manufacturing, and workforce development" (The White House, 2022c). This announcement noted that, while the United States produces approximately 10% of the world's supply of semiconductors, it currently produces none of the most advanced devices. Canada has some capacity for research and prototyping in this area, but largely lacks the facilities to participate in this market in a meaningful way. However, a 2023 agreement between Canada and IBM increases Quebec's role in the semiconductor supply chain in North America (Platt, 2023).

Canada has expertise in photonics, which can be useful in a range of quantum devices

The science of photonics applies to a wide range of devices, including consumer electronics (e.g., laser-based technology), communications technologies (e.g., fibre optics), biosensors, and LIDAR, and it continues to be a highly active area of research (Moody *et al.*, 2022). Photonics is concerned with the manipulation of light; photons — quantized parcels of light — can be prepared in a variety of ways (e.g., polarization, energy, coherence) and used to encode information or control other kinds of particles. In the context of quantum technologies, photonics can take on many roles. Photons can serve as qubits or be used to control some types of qubits; facilitate the transfer of quantum-encoded information; or be affected by their environment and subsequently detected and analyzed in the context of sensors. Generally, photonic technology may include high-performance lasers, single-photon sources and detectors, or other light-based devices found in quantum computers, communications technologies, and sensors.

There are bottlenecks in the photonics-based value chain, but several emerging technologies may help devices reach market readiness

A major issue across multiple photonics technologies is integrating the various components into on-chip designs (Moody *et al.*, 2022). For example, segments of devices that require significant cooling could benefit from reducing the number of connections to components outside the cooled regions. Different cooling technologies that do not require dilution refrigeration could then be used to cool less-sensitive areas of the device. Superconducting nanowire-based detectors work at cryogenic temperatures and could potentially be included on-chip. Another practical limitation of photonics involves photon emitters (on-demand photon output) and sources (probabilistic photon outputs). Specifically, increases to photon quality, efficiency, and rate, as well as integration into on-chip devices, would help with the development of photonic technologies. Frequency converters or other techniques for integrating different types of photonic devices could also help with the interoperability of different photonic technologies (e.g., trapped ion, neutral atom) (Moody *et al.*, 2022). This could aid in the design of devices that take advantage of different photonics technologies for different purposes within the same device, or to allow multiple devices to communicate with one another. Recent budget allocations announced by the Government of Canada may help advance some of these R&D targets (Box 3.3).

Box 3.3 Improving Semiconductor and Photonics Research, Development, and Fabrication

On-chip designs such as those required for quantum computers, sensors, and communications devices depend on advanced semiconductor and photonics technologies, which in many cases require specialized nano- and microfabrication facilities. In 2021, the Government of Canada announced it would invest $90 million to retool and modernize the NRC Canadian Photonics Fabrication Centre in Ottawa, which conducts its own research while also providing testing, prototyping, and pilot-scale manufacturing services to university researchers and businesses (ISED, 2022g). This commitment was increased in 2022 with a $150 million investment toward the development and supply of semiconductors.

3.2.4 Micro- and Nanofabrication

Quantum technologies rely on the manipulation of atomic and subatomic systems; in many cases, nano-scale devices are what control these systems. Manufacturing of devices that can operate on this scale requires advanced techniques and specialized facilities that are prohibitive for individual companies or research teams to access.

Canada has small-scale facilities appropriate for prototyping and research but cannot perform advanced fabrication at scale

Nanofabrication refers to a wide range of techniques that cover the manufacturing of components requiring features on the scale of nanometres. Because of these systems' small sizes and delicate nature, nanofabrication must be done in extremely clean facilities — a speck of dust can be 100 to 1,000 times larger than the design features required. Ensuring the appropriate level of cleanliness is expensive and requires large, specialized facilities with highly trained staff. As such, most companies outsource their nanofabrication work (Laucht *et al.*, 2021; INDU, 2022b).

In terms of access, management, and fee structures, nano- and microfabrication facilities can vary. Many universities and academic research centres offer access to otherwise prohibitively expensive infrastructure, along with the expertise to design, prototype, and produce many of the devices that make up quantum technologies. These smaller, more specialized facilities often focus on basic research and are most suitable for early-stage R&D. These facilities are largely publicly funded, partially subsidized, and tend to be located near regional research networks and universities with a strong quantum focus. Beyond academic and government centres, private research and technology companies also offer nanofabrication services. The ways facilities treat IP vary. In some cases, publicly funded facilities may be obligated to make public the results of their activities, while private facilities are more likely to keep results secret (NanoFabNet, 2021). However, few if any of these facilities can produce devices at scale.

Third-party organizations are closing technical gaps by linking companies to micro- and nanofabrication, R&D services, and talent

CMC Microsystems, a not-for-profit organization, facilitates connections between companies and other organizations to help bridge these technological gaps. It provides design, fabrication, production, and awards for projects carried out at one of several research and fabrication facilities. CMC Microsystems also manages Canada's National Design Network (CNDN) — a Major Research Facilities and Canada Foundation for Innovation (CFI) Major Science Initiatives (MSI) awardee — which is composed of 10,000 academic participants and 1,000 companies (CMC Microsystems, 2022). Similarly, C2MI in Bromont, Quebec specializes in microelectromechanical systems (MEMS), semiconductor assembly and testing, printed electronics, analytical services, and expertise to support potential customers (C2MI, n.d.). The National Optics Institute (INO), another Quebec-based supporting company, specializes in optics and photonics-based technologies through four business units: Biomedtech; Defence, Security, and Aerospace; Sustainable Resources, Agriculture, and Infrastructures; and Advanced Manufacturing (INO, n.d.).

The NRC has 42 advanced manufacturing facilities across Canada, including two for additive manufacturing and six for advanced materials (NRC, 2022f). One notable facility is the Nanotechnology Research Centre in Edmonton, which boasts expertise in micro- and nanofabrication, optoelectronics, chemical synthesis, and advanced instruments enabling experiments and fabrication beyond what is possible with most commercial setups. Some instruments are made available to clients and collaborators to use directly; the facility also employs experienced staff who can consult on and carry out experiments and tests themselves (NRC, 2022g). The Nanotechnology Research Centre includes a microscopy facility along with nanomaterial deposition and characterization facilities, as well as collaborative research programs (e.g., NRC-University of Alberta Nanotechnology Initiative, NRC-Waterloo Institute for Nanotechnology Collaboration) (NRC, 2022d, 2022e, 2022h).

Larger Canadian quantum companies have noted that their need for specially-fabricated components exceeds the capacity of any Canadian facility, forcing them to outsource to foreign companies. In some cases, this has led larger companies to explore domestic solutions, including internal production programs to strengthen their own supply chains and ensure compatibility among the components that make up their products (INDU, 2022b). Industry representatives also note that strengthening Canada's fabrication ecosystem would both increase the access Canadian companies have to fabrication services and attract business from international companies (INDU, 2022b).

3.2.5 Quantum Computing Value Chain

The computing value chain can be divided into *core* and *non-core* value chains, where the former is closely related to hardware and the latter includes software and services that support the operation of a quantum computing system; they are both needed for the adoption of these systems (PAC, 2019). This divide is comparable to classical computing, where core products are analogous to those produced by manufacturers of computers and hardware, and non-core refers to those products that catalyze the adoption and usefulness of core products (e.g., killer apps, services). Notably, the quantum computing core value chain is largely based on co-operation among state-funded fundamental researchers, large companies, and start-ups. Companies will often operate in either the core or non-core value chain; however, some currently operate in both.

The prevalence of companies associated with different segments of the value chain may be useful as a metric for the maturity of the sector

PAC (2019) estimated that 20% of the classical computing industry could be considered hardware-focused (in other words, core). For quantum computing, it estimated that number to be closer to 66%. In general, quantum-computing hardware is far from market-ready, still requires large capital investment, is beholden to ongoing fundamental and applied research, and consequently experiences long project lifecycles — whereas the non-core market may require less overhead and have shorter development lifecycles. It is predicted that non-core products will eventually overtake core value chains as the larger of the two market segments, though not until hardware infrastructure becomes more settled (PAC, 2019).

The core value chain is dominated by large international companies

The core value chain is not particularly welcoming to start-ups; entry into the market typically requires large capital investment, high levels of technical expertise, and the ability to develop projects with very long lifecycles. Generally, companies that exist in this market are multinational giants such as Amazon Web Services, Honeywell, and IBM (which could present challenges as the market develops, related to IP and Freedom to Operate concerns, as discussed in Chapter 5). However, not all links in this chain are in the business of building their own quantum computer; rather, they can include (i) infrastructure, (ii) quantum hardware, and (iii) connection management platforms — all things needed to support the development and production of the actual quantum computing device (PAC, 2019; MacQuarrie *et al.*, 2020). The following sections will consider components unique to the quantum computing market.

The primary bottleneck in the core value chain is qubit design and control

In terms of components in the quantum computing core value chain, one particularly formidable bottleneck is the qubit engine (or quantum system) itself. While a number of operational quantum computing systems exist, so far there has not been a universally accepted demonstration of quantum advantage over classical computers. Other platforms based on different types of quantum systems are in development but not yet available to potential users. In all cases, significant R&D funding is required to advance the state of these quantum systems before any can provide a market advantage to users (Hoofnagle & Garfinkel, 2021). The panel notes that, eventually, quantum computing may follow the lead of classical computing, with a few core product companies coming out "winners;" it will either push out or consolidate competitors, eventually optimizing (and shrinking) the rest of the core supply chain. However, different quantum systems may prove to be advantageous over others for certain applications.

The non-core value chain is easier for start-ups to enter but depends on core providers and end-users

Figure 3.8 categorizes non-core components of the quantum computing value chain in terms of tools, applications, additional systems, and services. While non-core products and services are currently niche (considering that computing hardware is still largely not market-ready), they include those that can drive the adoption of quantum computing by companies that do not necessarily have the expertise to develop their own business solutions.

Tools	Applications	Additional Systems	Services
• Quantum software development and benchmarking tools • Integration software • Databases	• Quantum algorithms • Data analytics • Models and use cases	• Quantum simulation • Cloud computing • Cybersecurity • Communications	• Education and training • Professional services • Outsourcing and cloud services

Adapted with permission from PAC (2019)

Figure 3.8 Components of the Quantum Computing Non-Core Value Chain

Links in the non-core value chain are generally less resource-intensive and have shorter project lifecycles (PAC, 2019). This makes it a particularly suitable market for start-ups to enter; consequently, many of the companies comprising Canada's quantum ecosystem exist in the non-core value chain. As with classical computing, non-core companies in quantum computing are those that offer software, tools, and services to augment the products (i.e., hardware) made available through the core value chain, often acting as the connection between core services and users or consumers. This also includes services that allow quantum computing to interface with existing and classical technologies. In the panel's view, while some Canadian companies have shown leadership in developing quantum computing hardware, the current quantum landscape in Canada may be better suited to SMEs that focus on the non-core value chain.

4

Ethical, Social, and Institutional Challenges

Chapter Findings

- Ethical challenges arise due to the ability of quantum technologies to cause or exacerbate security, privacy, and environmental risks and expand the digital divide. The positive impacts of quantum technologies can be fully realized if existing and proposed policies anticipate these challenges and advance the ethical research, development, and adoption of quantum technologies.
- Abuse of market power by established firms may lead to disparities in access to quantum technologies.
- Quantum technologies can offer efficiency and security benefits, but their uptake in the Canadian private and public sectors is inhibited by shortcomings in the federal procurement process and uncertainties surrounding technology usefulness, maturity, and interoperability.
- Qualified personnel with diverse educational backgrounds and experiences are instrumental in driving the adoption of quantum technologies. Educational, immigration, and socioeconomic barriers limit the opportunities for training, upskilling, and retaining the workforce.
- A lack of competition in Canada's telecommunications sector reduces incentives for established incumbents to leverage quantum technologies to achieve competitive advantage.

Quantum technologies can provide many benefits to the Canadian economy, research communities, and society. Their uptake and social acceptance, however, are subject to the ability of public and private actors to proactively address a number of social and ethical challenges that hinder adoption or that may arise later, once quantum technologies reach a certain level of widespread use. These challenges fall into two broad categories: (i) those that *emerge* due to new forms of conduct and expanded boundaries of what is possible (these include risks to digital infrastructure and privacy, potential environmental impact, and exploitation of misleading views about quantum technologies), and (ii) those that *already exist* but will be exacerbated by quantum technologies' ability to optimize familiar processes (including surveillance and automated decision-making) and expand the digital divide. The review of challenges presented in this chapter is the first part of a broader analysis of the multifaceted ethical, legal, social, and policy implications of quantum technologies, also known as *Quantum ELSPI* (Kop, n.d.). This chapter focuses on social and ethical issues within the framework of Quantum ELSPI. Chapter 5 reviews the interconnected legal and policy implications.

The chapter concludes by unpacking some institutional challenges that impede the uptake of quantum technologies by potential users, focusing on a lack of public and private leadership and interest, and the dearth of qualified personnel in the adopting sectors.

4.1 Ethical Challenges and Quantum Ethics

Like many other technologies, quantum technologies can have both beneficial and harmful applications. For example, quantum-resistant cryptography (QRC) can enhance individual and collective privacy and security, but the ability of quantum computers to overcome existing cryptography can facilitate mass surveillance and access to confidential information and undermine digital infrastructure essential for healthcare, banking, and public utilities. Quantum technologies can enable scientific breakthroughs in medical research and chemistry, but some actors can exploit the complexity of underlying quantum phenomena to spread misinformation and undermine public trust in scientific progress. Additionally, disparate access to quantum technologies and the expertise necessary for their adoption can exacerbate the digital divide among different communities, regions, and countries.

Due to the relative novelty of quantum technologies, ethical principles guiding human conduct in the face of both beneficial and harmful applications are only beginning to emerge. *Quantum ethics* is a new field of applied ethics that focuses on moral behaviour in the domain of quantum technologies (Kop, 2021a). It "calls for humans to act virtuously, abiding by the standards of ethical practice and conduct set by the quantum community, and to make sure these actions have desirable consequences, with the latter being higher in rank in case it conflicts with the former" (Kop, 2021a).

According to Brey (2017), several methodologies can be used to develop the standards of ethical conduct for emerging technologies (Figure 4.1).

Source: Brey (2017)

Figure 4.1 Ethics of Emerging Technologies

Generic approaches examine broad characteristics of technology, regardless of any specific applications. **Experimental approaches** see the introduction of a new technology into society as a process with inherently uncertain consequences. Instead of asking, "Is this technology morally acceptable?", they ask, "Is it ethically acceptable to experiment with this technology?" **Anticipatory approaches** combine ethical analysis with "foresight, forecasting or futures studies techniques" to predict and analyze ethical issues arising due to possible applications of emerging technologies. Risk analysis can be seen as a subset of anticipatory approaches that includes risk assessment, risk management, and risk-benefit analysis. **Participatory and deliberative approaches** rely on the public or stakeholders to give "an ethical or ethically informed assessment of an emerging technology" (Brey, 2017).

Anticipatory approaches have been endorsed by a number of researchers working in the area of emerging technologies (e.g., Johnson, 2011; Scott & Selin, 2019; Scott & Barlevy, 2022). According to Brey (2017), anticipatory approaches promise the most comprehensive assessments of emerging technologies due, in part, to their ability to incorporate risk analysis, generic, and participatory and deliberative approaches. Anticipatory approaches are foundational to the emerging framework for the responsible adoption of quantum technologies, which consists of quantum impact assessments, data protection and governance, access controls, soft law mechanisms, and responsible research and innovation (Chapter 7).

4.2 New and Emerging Ethical and Social Challenges

More widespread adoption of quantum technologies is accompanied by new ethical and social challenges, which arise because commercial applications can support new forms of conduct and expand the boundaries of what is possible. These challenges include risks to digital infrastructure and data breaches, potential environmental impacts, as well as the exploitation of misleading views about quantum technologies.

4.2.1 Security and Integrity Risks for Digital Infrastructure

The retroactive decryption of personal data and communications presents privacy risks

One privacy risk related to quantum computers is their potential to undo frequently used public key encryption systems that are not yet decryptable. According to Campagna *et al.* (2015), the following categories of security controls are at risk of being breached by a quantum computer:

1. *Any cryptosystem that is built on top of the mathematical complexities of Integer Factoring and Discrete Logarithms. This includes RSA, DSA, DH, ECDH, ECDSA and other variants of these ciphers. It is important to point out that almost all public-key cryptography in fielded security products and protocols today use these types of ciphers.*
2. *Any security protocols that derive security from the above public-key ciphers.*
3. *Any products or security systems that derive security from the above protocols.*

Encryption protects two types of personal data: stored data (i.e., data-at-rest) and data that are sent over the internet (i.e., data-in-flight). Some researchers suggest it is relatively easy to create quantum-resistant data-at-rest systems, and many modern encryption systems already address a possible risk of decryption (Hoofnagle & Garfinkel, 2021). Quantum computers will most likely jeopardize data-in-flight that were sent over the internet at some point in the past and captured and archived by non-governmental actors or intelligence agencies (Hoofnagle & Garfinkel, 2021). Although there is no publicly accessible and reliable information on the ongoing interception of data-in-flight, it is reasonable to assume that any message transmitted anywhere in the world might be captured and stored by some person or agency, and then unlocked at some point in the future (Mosca & Munson, n.d.). While this risk is real, it may also be overstated, because conducting cryptanalysis will require access to a powerful quantum computer, as well as time to perform the analysis (Hoofnagle & Garfinkel, 2021).

A quantum computer can crack the public keys of the infrastructure underpinning important societal functions

Public-key encryption supports vital internet functions. It is used to secure financial and commercial transactions and to authenticate users and websites (Box 4.1). In theory, if a quantum computer could be used to decrypt the public keys of encrypted messages, it could also break those of the infrastructure underpinning healthcare, financial, and industrial systems (Hoofnagle & Garfinkel, 2021; DeNardis, 2022).

Box 4.1 Some Applications of Public-Key Cryptography

Hypertext Transfer Protocol Secure (HTTPS) validates the authenticity of secure websites. This authentication process — which also depends on third-party certificate authorities to verify sites and provide browser keys — is the essential infrastructure for accessing sites and performing online transactions (DeNardis, 2022). If the certificate is compromised, an attacker could pretend to be a bank or regular user, get access to a user's bank account, secretly turn on a computer's microphone and camera, or search a user's files (Hoofnagle & Garfinkel, 2021).

The Internet Key Exchange protocol enables the IP Security (IPsec) protocol, which, in turn, is used to build virtual private networks (VPNs) (Felsch *et al.*, 2018). IPsec is used across the internet for essential tasks, "such as keeping information confidential, providing access control, authenticating data sources, and assuring data integrity" (DeNardis, 2022). IPsec-protected communications are often used by enterprises whose employees access company resources remotely (Felsch *et al.*, 2018).

Domain Name System Security Extensions (DNSSEC), which are based on the RSA public-key cryptosystem, were designed to protect the worldwide Domain Name System (DNS) from cyberattacks (DeNardis, 2022). DNSSEC applies public-key cryptography to the DNS so it can certify that the information resolving the domain name into an internet address to locate the site originates authentically from that site (DeNardis, 2022). Cyber threat actors could use false DNS information to direct users to fake websites in order to commit fraud and financial crimes.

4.2.2 Environmental Impacts of Quantum Technologies

Low-dimensional materials and nanomaterials (e.g., zero-dimensional semiconductor quantum dots, semiconductor nanowires, carbon nanotubes) hold promise for quantum technologies (Alfieri *et al.*, 2022). Nanomaterials can, among other things, improve the coherence of qubits and the purity and brightness of quantum emitters, serving as conduits for quantum sensing and imaging (Alfieri *et al.*, 2022). They are, however, double-edged swords. The unique properties that make them beneficial for product development, such as their size and high reactivity, also create environmental and safety concerns (NIEHS, 2021). For example, nanotechnology can allow sensors to find the smallest amounts of chemical vapours; however, it is often impossible to detect the level of nanoparticles in the air. This property presents a concern for the health and safety of employees in workplaces that use nanomaterials (NIEHS, 2021). Moreover, the use of nanomaterials by the quantum industry can increase the number of nanoparticles released into the environment.

The main challenges in conducting research on nanoscale materials include determining their quantity, evaluating biological reaction, and measuring the level of exposure and risk (NIEHS, 2022). In 2022, Environment and Climate Change Canada and Health Canada published their draft Framework for the Risk Assessment of Manufactured Nanomaterials under the Canadian Environmental Protection Act, 1999 (CEPA) (ECCC & HC, 2022). The framework provides that conclusions reached about a substance through the assessment process may differ, depending on its form (e.g., the traditional chemical or nanomaterial form, or variations among different nanoscale forms). Government scientists intend to use a weight-of-evidence approach to decide whether a nanomaterial released in the environment is considered toxic under CEPA (ECCC & HC, 2022). If adopted, the framework may determine how the government will regulate nanomaterials used in quantum technologies, including applicable environmental and human health risk assessments. As of September 2023, the draft framework has not been adopted.

4.2.3 Exploitation of Misleading Views About Quantum Technologies

Quantum technologies are fundamentally different from other disruptive technologies, such as nanotechnology or AI, due to their perceived ability to operationalize the principles of quantum mechanics (Chapter 1). While the proliferation of quantum technologies (and quantum computers' ability to solve some classically hard problems) has generated interest in the principles of quantum mechanics, specialists — let alone non-specialists — have difficulty understanding and explaining how quantum technologies work and what they might be able to achieve (Aaronson, 2021). For example, a public dialogue exercise conducted in 2017 in the United Kingdom found that the public was familiar with the word *quantum* but had limited understanding of how it applied to quantum technologies (EPSRC, n.d.). Quantum research is dominated by specialized public and private organizations, including defence and intelligence agencies, which contributes to the aura of mystery and secrecy surrounding quantum technologies.

Exploitation of misleading views about quantum technologies can stoke fear and undermine public trust

Some actors can exploit the scientific complexity of quantum mechanics to facilitate the spread and public acceptance of misinformation[11] about quantum technologies, which may lead to public controversies. Lessons can be learned from incidents fuelled by misinformation, such as the attacks on 5G towers in the United Kingdom (Parveen & Waterson, 2020), anti-vaccination attitudes, and the attempted bombing of IBM's nanotechnology facility in Switzerland (WEF, 2022b).

In addition to causing reputational or even physical harm to researchers and organizations working in the area of quantum, misinformation could erode public trust in quantum technologies (WEF, 2022b). In this context, bolstering public trust may require allocating public funds to confirm already-settled research findings. For example, in the European Union, genetically modified (GM) food safety research has received significant funding due to public controversies about genetically modified organisms (GMOs) (Ryan *et al.*, 2020). Between 1982 and 2010, the European Commission spent over €300 million on GMO safety research, leading scientists to conclude that biotechnology was not riskier than commonly used plant breeding technologies (E.C., 2010).

Quantum hype may be detrimental to technology adoption

The adage known as *Amara's Law*, coined by American researcher and technology forecaster Roy Amara, states that:

> *We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run.*

Over the long term, it is exceedingly likely that quantum technologies — and quantum computing in particular — will be incredibly disruptive and transformative, impacting society in ways that cannot currently be predicted. However, as with many technologies, there is a great deal of hype around quantum

11 Misinformation encompasses "false or misleading information that is inadvertently shared (misinformation), as well as false or misleading information that is deliberately created or shared (disinformation)" (CCA, 2023).

technologies. Broadly speaking, hype refers to "inflated, excessive or misleading claims" about the capabilities of various quantum technologies, or their usefulness or transformative potential for certain applications or industries (Ezratty, 2022). Such claims frequently come from quantum technology vendors and analysts promising profits to corporate customers and investors, and can be driven by inflated expectations about the potential market for quantum technologies. Hype about quantum technologies may also be driven by the relatively inscrutable nature and inherent "strangeness" of quantum phenomena, which can lead to "magical thinking" and references to science fiction (Ezratty, 2022).

Technology hype is not inherently bad; it can help drive research and innovation as well as attract funding from both the private and public sectors. However, hype that overpromises and underdelivers can also have a negative impact on progress in the field, leading to cuts in research and investment, and potentially creating a "quantum winter" similar to the "AI winter" of the 1980s and 1990s (Hoofnagle & Garfinkel, 2021; Ezratty, 2022). In the panel's view, concerns about a "quantum winter" in the near term are likely unfounded, given the high level of geopolitical competition in quantum technologies.

Doubts about the promise of quantum technologies among policy-makers could lead to the unpreparedness of critical infrastructure for the advent of quantum computing. For example, delays in the adoption of QRC would be detrimental to cybersecurity and individual and collective privacy. This potentially harmful effect of hype highlights the need for evidence-based policy responses to risks and opportunities presented by quantum technologies. Avoiding over-hyping in messaging about quantum technologies is one of several tactics for limiting the spread of misinformation and increasing public trust in quantum science within the framework of responsible research and innovation (Chapter 7).

4.3 Existing Ethical and Social Challenges Exacerbated by the Adoption of Quantum Technologies

The widespread adoption of quantum technologies could exacerbate a number of familiar ethical and social challenges, including privacy violations, individual and collective discrimination, and other forms of unfairness; it could also expand the digital divide due to, among other things, disparities in access to quantum technologies.

4.3.1 Privacy Violations

Quantum sensing presents privacy risks

The greatest near-term risk to privacy comes from advances in quantum sensing (Hoofnagle & Garfinkel, 2021). As some quantum sensing devices become smaller and less expensive, they can be used to enhance intelligence gathering and surveillance in public spaces. For example, quantum illumination may facilitate constant and ubiquitous surveillance and filming of people in dark spaces and at night. Similarly, sensitive magnetometers will allow for the detection of concealed (e.g., in a home or vehicle) or exposed objects from a distance. Unlike physical searches, which target certain people or objects for a limited time, a quantum-sensor search might happen covertly, at a distance, and continuously. With sensing's power to see through roofs and walls, or even into the human body, physical barriers become ineffective countermeasures against quantum-facilitated privacy intrusions (Hoofnagle & Garfinkel, 2021).

Powerful surveillance devices developed for intelligence and military purposes can be used by local law enforcement agencies to collect data and information about people's everyday lives (Koller, 2019). Often, they are used covertly and raise democratic oversight and accountability concerns (Crump, 2016; Robertson *et al.*, 2020) (Box 4.2).

Box 4.2 The RCMP's Use of Spyware Devices

In 2022, the House of Commons Standing Committee on Access to Information, Privacy and Ethics began a special study of spyware devices and software that the RCMP uses to conduct surveillance or collect data during investigations (Aiello, 2022). Concerns emerged after the House of Commons of Canada received documents that described how the police were "covertly and remotely" using spyware to access the text messages, private communications, microphones, and cameras of suspects' phones instead of using wiretaps or "other less intrusive investigative techniques" (Aiello, 2022).

In light of these developments, members of Parliament and the Canadian Civil Liberties Association were concerned about a lack of information on how and in what circumstances law enforcement uses spyware in targeted investigations. In particular, McPhail (2022) asked:

- *What kinds of investigations are deemed serious enough to use such invasive tools?*
- *What tools are being used, and who supplies them?*
- *What are the internal decision and authorization processes undertaken to authorize this nuclear option for surveillance of Canadians?*

Powerful sensing technologies developed for law enforcement purposes can also end up in the hands of private actors, exacerbating accountability and transparency concerns. For example, signals intelligence (SIGINT) is considered an inherently governmental function (Weinbaum *et al.*, 2017). Historically, only governments had the resources and legal authority to conduct SIGINT activities to gather intelligence from communications, electronics, or foreign instrumentation. Over time, SIGINT technologies became commercially available. They can now be used by private actors to engage in activities that present privacy and national security risks, such as "radio frequency (RF) spectrum mapping; eavesdropping, jamming, and hijacking of satellite communications; and cyber surveillance" (Weinbaum *et al.*, 2017). Investigations into the use of mercenary spyware suggest that private technologies facilitate state-sponsored intelligence gathering and surveillance activities (Deibert, 2022). In the future, private technology companies could exploit opportunities offered by quantum technologies for illicit purposes.

Quantum sensemaking presents risks to constitutional rights and freedoms, as well as privacy

Intelligence services, law enforcement, and other actors can subject data and information to quantum-enhanced scrutiny and contextualization, also known as the process of *sensemaking* (Hoofnagle & Garfinkel, 2021). For example, single-quanta sensors combined with machine learning might improve blind signal separation, a technique used to attribute voices to speakers in loud and crowded environments. Historically, the relative anonymity of the crowd protected the identities of participants of mass demonstrations from law enforcement, employers, and other groups and organizations that could inflict harm on protestors. By reducing the risk of retaliation, anonymity enabled "the exercise of the fundamental freedoms of expression, peaceful assembly, and association" (Robertson *et al.*, 2020). The ability of blind signal separation instruments to identify individuals based on the sound of their voices at a public gathering minimizes privacy protections afforded by the anonymity of the crowd and may have a chilling effect on constitutional rights and freedoms.

Moreover, quantum computing could be used to optimize machine-learning analytics instruments that purport to predict personality (Hoofnagle & Garfinkel, 2021). Social media companies, advertisers, credit-reporting agencies, insurance companies, and other businesses with surveillance incentives will be able to take advantage of quantum computers to create more accurate profiles of individuals and analyze more historical data. Quantum computers are likely to perpetuate the commodification of personal data (Zuboff, 2019; Krishnamurthy, 2022), making "individuals' desires, personalities, and lives more legible to powerful decisionmakers" (Hoofnagle & Garfinkel, 2021). Ultimately, quantum computing will intensify the existing power imbalances, as ordinary people will not have equal access to more efficient technologies and better information to scrutinize companies (Hoofnagle & Garfinkel, 2021).

4.3.2 Quantum Technologies and the Digital Divide

Abuse of market power by established firms may lead to disparities in access to technology

Research conducted in the United States shows that large firms use proprietary information technology to increase their market dominance (Bessen, 2022a). Considerable investments in proprietary software by financial institutions, retail, and insurance companies allow large firms to beat their competitors, including innovative start-ups (Bessen, 2022b). In addition to financial resources, big companies also leverage a large customer base, complementary services, and big data analytics to enhance their proprietary technologies, supress innovations introduced by smaller, newer companies, or stifle those companies' growth (Bessen, 2022b).

Despite the growing number of start-ups and SMEs in the quantum sector, it is following the trend of digital markets, with big technology firms — Microsoft, Amazon, Google, IBM, Intel, and Quantinuum (collectively termed "MAGIIQ") — establishing and maintaining their dominance (MacQuarrie *et al.*, 2020; Dekker & Martin-Bariteau, 2022). These companies can increase their customer base by acquiring smaller quantum computing firms to eliminate potential competition or by offering access to quantum processors through quantum computing as a service (QCaaS) (Dekker & Martin-Bariteau, 2022). Having established market dominance, MAGIIQ can influence the ability of people and organizations to access QCaaS by dictating prices and terms of use. The concentration of QCaaS in the hands of several companies may lead to disparities in access to technology between economically advantaged and disadvantaged groups, and among users in different countries and regions of the world. The abuse of market power is particularly relevant for users in Canada, because most of the big firms providing access to quantum technologies are foreign-based. This vulnerability is compounded by Canada's relatively weak competition policy. The application and enforcement of competition law may favour major market players as long as they exercise their power in compliance with the law (Chapter 5).

There is a lack of government support for quantum production and diffusion across the country

According to the *National Quantum Strategy* (NQS), the Government of Canada will provide $70 million in financing for quantum firms through a network of regional development agencies. Pacific Economic Development Canada, Prairies Economic

Development Canada, and the Federal Economic Development Agency for Southern Ontario began accepting applications in 2022, with Quebec also due to receive funding (Hemmadi, 2023; ISED, 2023d). Meanwhile, some regions are omitted from the funding scheme — as noted in Chapter 3, the concentration of quantum companies and researchers in certain regions can lead to disparities across the country; end-users located in quantum clusters may have access to resources and expertise that facilitate technology diffusion and adoption. Although remote access may democratize the availability of quantum computing, the application of technology to specific tasks (e.g., simulation, optimization) requires end-user expertise, which may be distributed unevenly across the country. Without special policy interventions, clustered technology diffusion could deprive some regions and communities of the opportunity to fully realize the economic and security benefits offered by quantum technologies, thereby worsening the digital divide.

Disparities in access to secure communications can exacerbate the digital divide

Technology that uses cryptography to secure communications is crucial to data protection, access to information, and freedom of expression. Encryption protects private data and opinions from outside surveillance, which is particularly important in some political and legal environments (Kaye, 2015). In light of significant cybersecurity risks linked to quantum computing, participants of public consultations on quantum technologies in the United Kingdom expressed concerns about the digital divide between those who will have access to quantum-resistant communications networks and those who will not (EPSRC, n.d.).

In Canada, for example, the NQS provides that a land- and satellite-based "national quantum communications network combined with post-quantum cryptography" could improve the security of infrastructure and information sharing (ISED, 2023d). However, the Government of Canada's efforts to deliver universal high-speed internet connectivity across the country has not achieved equitable access to digital infrastructure, leaving some rural and remote regions at a disadvantage (CCA, 2021).

On a global scale, new network infrastructure available in some developing countries could reduce the cost of upgrades to QRC. However, global disparities in access to technology and expertise will likely result in high-income countries gaining a "strategic advantage, while other nations fall into 'quantum poverty'" (WEF, 2020). Quantum scientists in high-income countries, for example, are working on hybrid data storage solutions that combine classical and quantum encryption, and on developing communications networks that can be scaled to apply in local and metropolitan areas (VeriQloud, n.d.-a, n.d.-b). Protectionist trade and intellectual property (IP) policies aimed at ensuring national quantum advantage can further stifle international collaborations and equitable access to technology. The digital divide could act as a significant barrier to unlocking the full economic and societal benefits of quantum technologies (WEF, 2020).

The adoption of quantum technologies may lead to job transformation or loss

Robotics, AI, and other forms of automation and workflow optimization are a double-edged sword. While they create demand for new jobs, they also make existing jobs obsolete or lead to automation-related job transformations. According to Frenette and Frank (2020), in 2016, 10.6% of workers in Canada were at high risk (70% or higher) of job transformation due to automation, and 29.1% were at moderate risk (between 50% and 70%). Several categories, including older workers (55 or above), those with no post-secondary education, or those employed in the manufacturing sector, were at a higher risk of being impacted by automation (Frenette & Frank, 2020). The results of a public dialogue on quantum technologies conducted in the United Kingdom show that job losses in analytical and logistical roles are perceived as pressing, near-term risks posed by quantum technologies (EPSRC, n.d.) (Box 4.3).

Box 4.3 The Port of Los Angeles Logistics Optimization

The Port of Los Angeles is the largest U.S. facility for handling shipborne cargo. An initiative at Pier 300, one of the port's largest terminals, leveraged D-Wave's computational power to optimize the port's logistics (D-Wave, 2022). The Hyper-Optimized Nodal Efficiency (HONE) engine processed data from more than 100,000 different cargo-handling runs across a range of real-world and hypothetical scenarios, in order to identify opportunities for optimization. As a result, the terminal uses nearly 40% fewer of its crane resources for the unloading process, and each of the cranes travels a considerably smaller average distance per day. The cranes have also increased their deliveries by more than 50%, and each truck is spending nearly 10 minutes less receiving the payload at the terminal (D-Wave, 2022). Arguably, a classical program could have been used to optimize logistics; the D-Wave annealing solution was chosen because the project team was familiar with it (QCR, 2022b).

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At the same time, the growing use of automation and robotics is a complex issue. It requires considering both the private sector's desire to increase the efficiency of supply chain management and the impacts of workflow optimization on the workforce. For example, to support the workforce of the Port of Los Angeles, the Government of California funded the Goods Movement Training Campus for truck drivers, mechanics, welders, and others who might require upskilling or re-skilling due to automation, and created professional development opportunities for future hires (Spectrum News 1, 2022).

4.3.3 Bias and Lack of Explicability

Quantum machine learning may exacerbate discrimination or other kinds of unfairness resulting from automated decision-making. Among the reasons existing AI systems generate skewed, inaccurate, or discriminatory results is because available datasets and models make AI biased by design (Robertson *et al.*, 2020; CCA, 2022; Crawford, 2022). Marginalized and racialized people and groups are disproportionately impacted by AI trained on *bad data* (i.e., missing, incorrect, or inconsistent data) (Richardson *et al.*, 2019). Researchers found that the use of AI to make hiring decisions discriminated against women (Dastin, 2018) and people with physical and mental disabilities (Fruchterman & Mellea, 2018). AI has perpetuated discrimination against Black people in various contexts, including healthcare (Obermeyer *et al.*, 2019), the criminal justice system (Robertson *et al.*, 2020), and online content moderation (Sap *et al.*, 2019). In Canada, data collection and processing practices often discriminate against Indigenous communities (Robertson *et al.*, 2020) and minimize or disregard Indigenous knowledges and experiences (CCA, 2022). The existing funding models enable select institutions to define the research agenda and extract Indigenous data while downplaying the potential negative impacts of these practices for Indigenous communities (GC, 2019).

A lack of gender and racial diversity in STEM (Section 4.4.2) could also amplify bias in quantum-enabled automated decision-making systems. Lessons can be learned from many applications of AI — including facial recognition, speech recognition, and hiring tools — where a lack of diversity in the AI industry has fed into data selection and technology design processes, resulting in outcomes that are biased against women and minoritized and racialized people (West *et al.*, 2019; Stinson, 2022).

The use of bad data to train quantum-enabled decision-making systems will exacerbate existing inequities due to an inverse correlation between the ability to learn and explain in machine learning (i.e., the most powerful learning systems find the least explainable and least predictable connections) (Hoofnagle & Garfinkel, 2021). Absent special governance measures, applications that are already prone to bias may become even more susceptible to it.

4.4 Institutional Challenges Inhibiting the Adoption of Quantum Technologies

Although quantum technologies are still in the early stages of development, some applications (e.g., sensing, metrology, and types of quantum computing) are mature enough to offer efficiency for security benefits to potential users. Despite these advantages, uptake in the Canadian private and public sectors remains relatively low. Obstacles such as the lack of public and private support or interest in quantum technologies, and the dearth of qualified employees in the adopting sectors can impede the speed and scope of technology adoption.

4.4.1 A Lack of Public and Private Leadership and Incentives

Governments can mobilize a number of instruments — such as procurement, consumer incentives, or regulatory standards — to stimulate demand for innovative products (Edler *et al.*, 2016; Meckling & Nahm, 2018). There are several benefits to implementing demand-side innovation policy instruments. First, in the aftermath of public spending cuts caused by the 2008 financial crisis, policy-makers have shown growing interest in demand-side innovation instruments, particularly for procurement, in order to increase the efficiency of public spending (Kundu *et al.*, 2020). Second, by shifting focus from producers to end-users, demand-side instruments could correct some weaknesses in Canada's supply-driven innovation policy, such as the lack of strategies for technology diffusion and reduced market ability to adopt innovations (Edler, 2019). Third, demand-side instruments would give governments more control over determining the direction of innovation policy (i.e., aligning it with important social, environmental, and economic challenges) (Mazzucato, 2018). Governments may, for example, leverage their "sophisticated demands and sufficient purchasing power" (Uyarra *et al.*, 2020) to lead the formation of quantum technology markets and determine the direction of their development. In the panel's view, this consideration is particularly relevant given the potential need for government intervention to address social and ethical challenges related to quantum technologies.

The Government of Canada has been slow to adopt instruments stimulating demand for innovation

Despite the benefits of demand-side innovation instruments, the Government of Canada has been slow to adopt them (Southin, 2022). An independent panel convened by the federal government in 2010 to review federal support for business R&D (GC, 2011) — also known as the Jenkins Panel — concluded that Canada was heavily dependent on supply-side innovation instruments that "offset the cost of inputs to the private firm's innovation process" (Southin, 2022), such as investments in R&D, skills, advice, and technical services (Edler *et al.*, 2016; Edler, 2019). In the Canadian context, supply-side instruments have failed to engage the private sector in innovation projects (GC, 2011; Breznitz, 2021). Despite significant public spending on R&D and science, Canadian industry demonstrates low levels of technology adoption and investments in innovation (Breznitz, 2021).

Technology start-ups and SMEs face difficulties in accessing federal procurement opportunities

Government procurement is the purchase of outside goods, services, and works by government departments and agencies. In Canada, government procurement accounted for 14.6% of national GDP in 2020 (OECD, n.d.). As such, it could be an important policy instrument to incentivize the adoption of quantum technologies, particularly when the private sector is not willing to act as first buyer (ISED, 2022d). However, Canadian start-ups and SMEs that work in quickly evolving technological fields note several policy obstacles that limit their ability to participate in the procurement process.

First, the dominance of incumbent technology suppliers makes it difficult for quantum start-ups to qualify for the federal government's contracts and enter the market, thereby limiting their Freedom to Operate (Chapter 5). SMEs that deliver goods and services to the federal government often share similar characteristics (OGGO, 2018). Usually, these businesses are established firms that grew prior to accessing federal contracting opportunities. These companies are, "disproportionately concentrated in the knowledge- and technology-based sectors, and in construction" (OGGO, 2018). Moreover, federal procurement opportunities are ill equipped for quantum technologies that are at the prototype stage and cannot comply with standard government requirements for readily available services or products (Donahue, 2009). The Government of Canada introduced new procurement programs that aim to offer more flexible conditions for emerging technologies; however, the small amounts allocated to these programs limit their ability to meaningfully affect the commercialization and adoption of quantum technologies (Chapter 6).

Second, the Government of Canada reaches out to the private sector when decisions on what technologies to procure have already been made, rather than at the outset of the procurement process (OGGO, 2018). Due to specific and prescriptive procurement requirements, only some companies familiar with the government procurement process can apply for federal offers. Moreover, it is challenging for purchasing government departments to draft less restrictive specifications for an innovative product without industry engagement. Industry can, however, provide knowledge and expertise on state-of-the-art technologies and solutions (OGGO, 2018).

Lastly, while some technology start-ups see early engagement as an opportunity to access government offers, others fear that introducing more back-and-forth into the procurement process will increase the cost of doing business because "government is increasingly using requests for information, industry consultation sessions, and releases of draft requests for proposals to solicit input from industry" (OGGO, 2018). From the perspective of some SMEs, "this is free consulting that takes time and money" (OGGO, 2018). Ultimately, early industry consultations can produce advantages for larger companies whose representatives can afford to participate in them.

New programs to boost the adoption of technologies by the public sector face challenges

Following the release of the Jenkins Panel report in 2011, the Government of Canada began to reform its innovation policy instruments, partially to increase the role of government procurement in technology adoption (Crisan, 2020). Budget 2018 consolidated some government innovation programs into Innovative Solutions Canada (ISC), administered by ISED (FIN, 2018). Under ISC, departments and agencies issue calls for proposals for SMEs to perform various services or deliver goods (Chapter 6).

Despite some successful projects, ISC is not meeting its spending objectives. In 2017, when the program was launched, the federal government was expected to spend around $100 million per year on different innovation projects (Hemmadi, 2022). In 2022, the allocated spending was increased to $113.8 million per year. Yet, over the course of four years, from March 2017 to March 2021, federal departments and agencies spent only $102.6 million on ISC challenges, which is less than what they were mandated to spend in 2022 alone. Much of ISC's spending deficit is attributed to DND, which is mandated to spend $65 million per year on ISC but spent only $3.38 million in the 2019–20 fiscal year and $4.9 million in the 2020–21 fiscal year. Partly, this is because DND's Innovation for Defence Excellence and Security (IDEaS) program is similar to ISC; the department spent almost $12.5 million under IDEaS in 2020–21 (Hemmadi, 2022). As of April 2022, IDEaS provided $8.2 million to innovators working on developing quantum sensing technologies (ISED, 2023d).

A lack of competition in the telecommunications sector may slow the adoption of quantum technologies

The telecommunications sector is often cited as one of the most likely early adopters of quantum technologies in Canada (Chapter 2). However, a lack of competition among domestic telecommunications providers may stifle the adoption of quantum technologies. Some research shows that the level of competition in a firm's market influences its decision about whether to rely on technological innovation as a primary business development strategy. High concentration levels can inhibit innovation by eliminating incentives created by competition (CCA, 2009). Using six indicators of market rivalry,[12] Geroski (1990) concluded that "actual monopoly has an unambiguously inhibiting effect, and that rivalry has an unambiguously stimulating effect on innovativeness."

There is very limited competition among Canada's incumbent carriers; what competition exists is largely due to regulatory intervention in the provision of wholesale services (CRTC, 2015, 2020). In this context, there may be little motivation for established incumbents to leverage innovation to compete for a share of the domestic market. A lack of competition in Canada's communications sector may negatively affect the adoption of technologies that could significantly improve the security of data and communications (e.g., long-distance QKD networks and QRC).

Canada's big banks adopt technological innovations implemented elsewhere, provided the risks and benefits are well known

Various reports cite the financial sector as one of the key adopters of quantum technologies (Chapter 2). However, as is the case with the telecommunications sector, the state of competition in the financial sector may affect the speed of adoption. On one hand, Canada's banking system has high concentration levels; the six largest banks, known as the Big Six (Bank of Montreal, Bank of Nova Scotia, Canadian Imperial Bank of Commerce, National Bank of Canada, Royal Bank of Canada, and Toronto Dominion), controlled around 90% of overall banking assets from 1996 to 2015 (McKeown, 2017). On the other hand, unlike the telecommunications sector, there is inconclusive evidence on the state of competition in the financial sector (Bednar *et al.*, 2022), and high concentration levels are not indicative of the degree of competition among incumbent firms or

12 The extent of market penetration by entrants, the market share of imports, the relative number of small firms, the change in concentration, the market share of exiting firms, and the concentration ratio.

market contestability (CCA, 2009). In a contestable market, firms willing to enter and exit the market do not face prohibitive barriers, and the prospect of nascent competition may encourage innovation by incumbent firms (CCA, 2009).

One study that measured the degree of contestability in the Canadian banking industry concluded that the sector is characterized by monopolistic competition (Allen & Liu, 2007), which disincentivizes so-called *visible innovations* (e.g., innovations in services) because they can be relatively quickly replicated by competitors, thus minimizing the advantages sought by the first innovator (CCA, 2009). As an alternative, innovation usually targets internal processes (e.g., physical capital and software for ICT), which are hidden from competitors and, therefore, harder to reproduce. For example, between 2009 and 2019, Canada's six largest banks collectively invested $100 billion in technology, substantially improving their in-house cybersecurity. This indicates that Canadian banks may be interested in investing in security-enhancing quantum technologies. However, the banking sector remains relatively risk-averse with respect to technological innovations. Usually, it adopts successful technological innovations implemented elsewhere, provided their risks and benefits are well known (the so-called *early follower innovation strategy*) (CCA, 2009).

Canadian SMEs face challenges when adopting new technologies

From 2015 to 2019, Canadian SMEs were responsible for over 50% of the value added to the country's GDP and, as of December 2021, represented 99.8% of domestic employer businesses (ISED, 2022b). Despite their significant role in the national economy, SMEs face challenges in achieving technological maturity, which, in turn, stifles their growth (Goldsmith, 2021). The most common factors delaying the digitization of SMEs are "[limited] access to infrastructure; low interoperability of systems; a lack of data culture and digital awareness; internal skills gaps; financing gaps for covering high sunk costs to transform; uncertainty about liabilities and responsibilities when engaging in new digital activities" (OECD, 2021b). A 2017 survey of nearly 1,000 Canadian manufacturing firms with under 500 employees, found that firms were encountering a host of obstacles to implementing new technologies such as sensors and production optimization software. The main obstacles were a lack of qualified employees (42%), excessive costs (38%), employees' resistance to change (31%), and unclear return on investment (31%) (Bédard-Maltais, 2017).

Interoperability issues slow the adoption of quantum computers and communications

Interoperability can be defined as the ability of devices produced by different manufacturers to work together (Gartner, n.d.). Two types of interoperability concerns slow the adoption of quantum computers. First, integrating quantum computers with existing IT systems requires new workflows that coordinate quantum and classical computing and address security, data management, and compliance issues (Zapata Computing, 2021, 2022). Second, potential end-users express concerns over the interoperability of quantum applications designed by different vendors with various hardware devices mixed with classical computing (Zapata Computing, 2021). Similarly, the success of a quantum internet depends on its interoperability with established protocols and infrastructures. Achieving “backward compatibility” and network integration requires collaborations among quantum innovators and experts already working on developing the internet’s core architecture (DeNardis, 2022).

4.4.2 A Lack of Qualified Personnel

Identifying the technical expertise needed in the quantum workforce of the future is challenging

While it is generally agreed that the quantum workforce will require a wide range of expertise, the specific needs of this developing market are not fully understood. This is made more challenging by the breadth of technologies, and the subject-matter knowledge required to design and implement new technologies (likely at all levels of innovation, from fundamental research to end use) (NSTC-SCQIS, 2022). Some estimates suggest that, as of December 2021, the demand for quantum computing experts was three times higher than the number of graduates who could fill open positions (Masiowski *et al.*, 2022). These estimates, however, are not specific to Canada and may not reflect its labour market dynamics. More targeted data collection and surveying on both the supply and demand side of the growing quantum workforce could help forecast what expertise will be needed by industry.

There is a dearth of education and training opportunities in quantum technologies

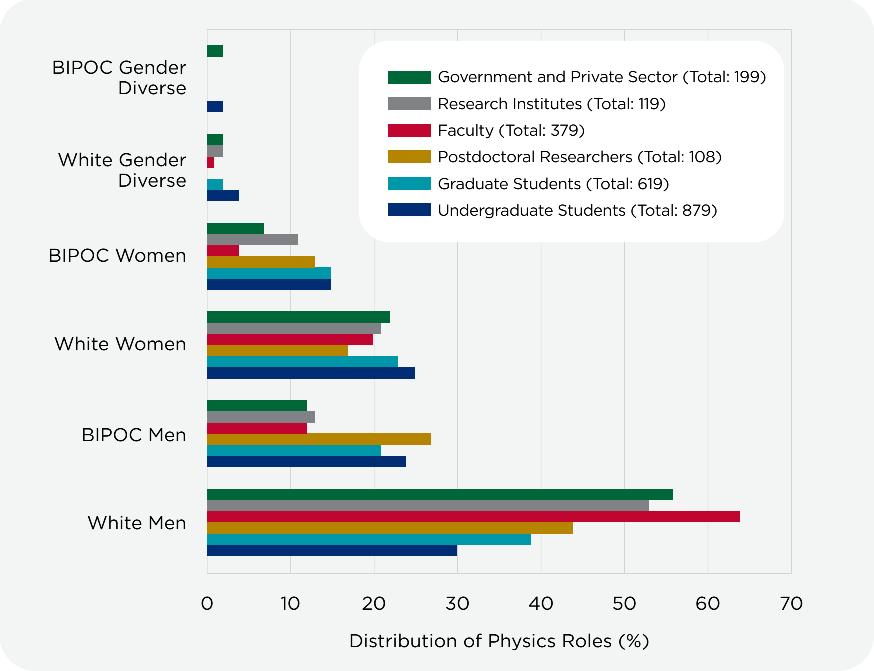
Research conducted by McKinsey in 2021 showed that a significant number of universities worldwide had research programs specializing in quantum technologies; however, relatively few universities (29 out of 176) offered master’s degrees in this field, with 41% of these programs offered in the United States (Masiowski *et al.*, 2022). One model estimates that a lack of master’s programs in quantum technologies limits the opportunities for upskilling 350,000 professionals who graduated with master's degrees in such fields as biochemistry, electronics and chemical engineering, ICT, and mathematics (Masiowski *et al.*, 2022). Moreover, as quantum technologies extend their reach into different adopting sectors, such as finance, telecommunications, healthcare, and pharmaceutical manufacturing, professional development programs for people with diverse educational backgrounds and experiences become increasingly important to facilitate technology diffusion (INDU, 2022a, 2022b).

There is a lack of diversity in STEM

The continued lack of diversity in STEM is another reason why skilled personnel are hard to find and why talent is not being used to its full potential. For example, Indigenous people make up less than 2% of all STEM sector employees (Cooper, 2020). Only 4.1% of Indigenous workers have post-secondary education in STEM disciplines compared to 10.4% of non-Indigenous people (Kazmi, 2022). Studies show that minoritized and racialized professors are underrepresented, have lower wages than their white colleagues, and feel that their contributions are undervalued by their peers (Henry *et al.*, 2017). Racialized professors also achieve tenure and promotions later than white men with comparable credentials (Wijesingha & Ramos, 2017). These studies anticipate systemic barriers and biases that racialized students in STEM fields, including quantum, might face. In addition, the lack of Indigenous, Black, and racially diverse mentors discourages underrepresented students from pursuing STEM majors and careers (Adams, 2021).

Math, computer science, and engineering are dominated by men

When it comes to attracting women researchers to quantum fields in Canada, "there is huge competition for the relatively few female candidates in quantum technologies, but this has not necessarily translated into more women entering relevant programs of study" (ISED, 2022d). While Canadian institutions have initiatives in place to encourage the enrolment of women in STEM fields, that engagement has remained low. For example, women accounted for 56% of post-secondary enrolment between 2010 and 2019. However, only 38.5% of STEM students were women, with even lower rates in math and computer science (28%) and engineering (22%) (Mahboubi, 2022). A 2021 demographic survey of the Canadian physics community found low numbers of women enrolled in math, computer science, and engineering (Smolina *et al.*, 2021) (Figure 4.2).



Data Source: Smolina *et al.* (2021)

Figure 4.2 Demographics of Respondents with a Physics Education in Canada in 2021

The survey was conducted online using a "snowball" sampling method, where participants were expected to recruit future participants. It received responses from across Canada, with the most (42%) coming from Ontario, followed by Quebec (18%), and British Columbia (16%). The survey asked respondents about their current position (e.g., graduate student, faculty), then asked them to self-identify according to race and gender. Undergraduates showed significantly more diversity than other cohorts; however, in all cases, white men were the most represented demographic.

These findings indicate that initiatives to increase the number of women in STEM may not be effective. One possibility is that policies fail to embrace intersectionality — one person's ability to hold several intersecting social identities that could negatively affect their chances for a successful career in these fields (Adams, 2021). For example, "women of colour experience a 'double-bind' of race and gender when negotiating barriers and challenges in STEM pursuits" (Adams, 2021). Human-centric employment, retention, and immigration policies — such as offering affordable childcare and better leave to all parents — are instrumental in attracting diverse candidates (ISED, 2022d).

There are problems in attracting and retaining international quantum talent

In cases where labour shortages present challenges for technology adoption, attracting international talent through immigration policies may be the fastest way to address the problem. However, employers in high-demand sectors, such as computing and telecommunications, experience difficulties and delays in getting work authorizations for highly skilled professionals to come to Canada. The backlog of applications at Immigration, Refugees and Citizenship Canada and the resulting processing delays are the main barriers experienced by employers when recruiting international talent (BCC, 2022; Singer, 2022). Other common barriers include complex bureaucratic procedures, overlapping federal and provincial/territorial policies, and administrative costs (BCC, 2022). In addition, companies in new and emerging sectors, such as quantum technologies, may experience difficulties in attracting international talent because there are few if any National Occupational Classification (NOC) codes for the positions they are trying to fill (Cameron & Faisal, 2016).

Employers in Canada also find it difficult to retain employees. Competition from other countries and difficulties faced by temporary skilled workers (including former international students) in obtaining permanent resident status are among the most common barriers to retaining international talent (BCC, 2022). In 2019, international students accounted for 28% of those enrolled in a STEM-related field. Looking at sub-fields, international students made up 33% and 40% of engineering students and math/computer science students, respectively (Mahboubi, 2022). About 3 in 10 international students who entered Canada in the 2000s became permanent residents within 10 years of having obtained their first study permit (Choi *et al.*, 2021). In some cases, it may be more feasible for graduates to return to their home country or look for opportunities in countries with more accessible and expedient immigration policies (Chapter 6).

5

Legal and Regulatory Challenges

Chapter Findings

- Canada's existing legal framework may protect people against some forms of quantum-based surveillance, but the adoption of quantum technologies will likely amplify legal challenges stemming from the identification of previously anonymized data and may undermine encryption as a defence against liability for data breaches.
- Established firms and first movers could use technical standards, IP protections, and competition rules to create market barriers for quantum companies and stifle the adoption of competitor technologies. Substantive amendments to, and better enforcement of, legal rules can address the economic and social harms arising from the dominance of select companies in the quantum market.
- Canadian and foreign trade regulators retain significant discretion over export and import controls governing technology, infrastructure, and materials. Regulatory discretion can have negative implications for Canadian quantum companies and end-users, limiting their access to global markets and supply chains.

In addition to the ethical and social considerations identified in Chapter 4, a quantum ethical, legal, social, and policy implications (Quantum ELSPI) framework also requires that attention be paid to legal and policy aspects. The adoption of quantum technologies gives rise to a number of issues, including enhanced surveillance capabilities, data de-identification and decryption, and abuse of market power by select companies. The panel examines Canada's privacy, IP, and competition law to outline different approaches to address identified risks, with an eye on substantive reforms and enhanced enforcement of applicable laws. It also explores the role of standards and domestic and foreign trade regulations in technology production, diffusion, and adoption, particularly as these relate to the Canadian market.

5.1 Reasonable Expectation of Privacy and Security of Personal Information

5.1.1 Reasonable Expectation of Privacy

While quantum sensors enhance public surveillance capabilities (Chapter 4), existing constitutional principles regarding the reasonable expectation of privacy (Box 5.1) are likely sufficient to address the use of quantum-based surveillance technologies such as thermal imaging and body cameras (Dekker & Martin-Bariteau, 2022).

Box 5.1 Reasonable Expectation of Privacy in Canadian Law

In *R. v. Tessling*, the Supreme Court's majority considered that the use of forward-looking infrared (FLIR) cameras by law enforcement for residential surveillance did not violate the property owner's reasonable expectation of privacy (SCC, 2004). Although FLIR cameras can detect sources of heat inside a home and allow law enforcement to gather information, they cannot identify the exact sources of that heat or "'see' through the external surfaces of a building" (SCC, 2004). Because of significant discrepancies between quantum sensors and FLIR, *R. v. Tessling* may not be applicable to quantum sensors (Dekker & Martin-Bariteau, 2022). Reflecting on the potential implications of technological advances on privacy, Justice Binnie noted that, as "the capability of FLIR and other technologies will improve and the nature and quality of the information hereafter changes, it will be a different case, and the courts will have to deal with its privacy implications at that time in light of the facts as they then exist" (SCC, 2004).

The evolution of surveillance technology over the past decade has had implications for the reasonable expectation of privacy for people in Canada. In *R. v. Jarvis*, Chief Justice Wagner stated that privacy is contextual and the "'reasonable expectation of privacy' is a normative rather than a descriptive standard" (SCC, 2019). Relying on Justice Binnie's reasoning in *R. v. Tessling*, the majority in *R. v. Jarvis* noted that "the privacy jurisprudence recognizes the potential threat to privacy occasioned by new and evolving technologies more generally and the need to consider the capabilities of a technology in assessing whether reasonable expectations of privacy were breached by its use" (SCC, 2019).

According to Dekker and Martin-Bariteau (2022), existing privacy frameworks provide a foundation for assessing whether any particular application of quantum sensing is reasonable "within the context of that technology's sensing capabilities (i.e., the degree of invasiveness on an individual's privacy)." For example, the technique of counterfactual ghost imaging (Box 5.2) shows how, from a legal standpoint, the use of a quantum sensing for surveillance is not significantly different from the use of any other surveillance technology. This technique allows a third party to collect information about a person without their consent and knowledge. The sensing technique, however, is irrelevant because the reasonable expectation of privacy test remains the same as long as certain factual circumstances are met. Such surveillance practices may be illegal both in the private and public sector contexts (Dekker & Martin-Bariteau, 2022).

Box 5.2 Counterfactual Ghost Imaging

Counterfactuality refers to using quantum effects to examine objects or transmit messages without exchanging matter or energy between the two parties when transferring information (Hance & Rarity, 2021). A single photon can be used to go through an interferometer (a device merging two or more sources of light to create an interference pattern) and identify an object or its characteristics without a physical interaction with it (LIGO Caltech, n.d.). A method called *ghost imaging* uses entangled photon pairs to detect obscure objects with significantly better "signal-to-noise ratio while preventing over-illumination" (Zhang *et al.*, 2019).

Still, evaluating privacy implications of quantum-based surveillance may present challenges for courts unfamiliar with this sensing technology. Quantum sensing comes with its own ethical considerations, and its application without guidance and oversight can lead to privacy violations. Proactive regulation and ongoing oversight could support the accountable use of quantum sensing by governments, law enforcement, and private actors (Dekker & Martin-Bariteau, 2022).

5.1.2 Protecting Personal Information

To the extent that quantum computing may optimize AI-driven profiling, predictions, surveillance, and decision-making (Chapter 4), it may also exacerbate the existing legal challenges pertaining to the regulation of algorithmic systems. One legal issue is related to the notion of personal information in Canadian privacy law. Several terms describe the range of information derived from humans, from completely anonymized to fully identified personal data (Box 5.3).

Box 5.3 The Spectrum of Data Derived from Humans

Anonymized data are "data in a form that does not identify individuals and where identification through [their] combination with other data is not likely to take place" (U.K. ICO, 2012).

De-identified data are data from which "the association between a set of identifying data and the data subject" has been removed (NIST, n.d.).

Pseudonymized data are a subset of de-identified data (OPC, 2016). During pseudonymization, "a coded reference or pseudonym is attached to a record to allow the data to be associated with a particular individual without the individual being identified" (U.K. ICO, 2012).

Personal data are data that identify an individual.

Quantum computing can exacerbate data re-identification issues

Canadian data protection law protects information that directly, or in combination with other information, identifies an individual (e.g., name, age, ID numbers, income, ethnic origin, opinions, evaluations, employee files, credit and loan records, medical records) (OPC, 2019a, 2019b). This list excludes anonymized data. However, some researchers argue that data anonymization is ineffective because a user can still be re-identified using data-mining techniques (Ohm, 2010). In the age of data science and AI, only sophisticated de-identification approaches can ensure privacy (Dekker & Martin-Bariteau, 2022). The use of quantum computing amplifies these risks and highlights the need for a data protection reform that considers the challenges of a growing data economy (Scassa, 2020).

The *Personal Information Protection and Electronic Documents Act* (PIPEDA) does not define anonymized data or outline specific provisions for their treatment

PIPEDA is a federal law governing private sector use of personal information in the course of commercial activities (GC, 2000). PIPEDA does not expressly define *pseudonymized data* or outline specific provisions for their treatment by organizations. The absence of such provisions distinguishes PIPEDA from the E.U.'s *General Data Protection Regulation* (GDPR), which sets a global standard for data protection. The GDPR differentiates between pseudonymized and anonymized data — it applies to the former but not the latter (ETHI, 2022). In Canada, the Federal Court decisions may suggest that pseudonymized data could be personal information under PIPEDA (OPC, 2016). However, given that the use of quantum computing may amplify the risks of data re-identification, the absence of clear legislative provisions on the status of anonymized data presents privacy risks for people in Canada.

Bill C-27 excludes anonymized data from data protection rules

In June 2022, the Government of Canada introduced Bill C-27 (*An Act to enact the Consumer Privacy Protection Act, the Personal Information and Data Protection Tribunal Act and the Artificial Intelligence and Data Act and to make consequential and related amendments to other Acts*) (House of Commons of Canada, 2022a). The *Consumer Privacy Protection Act* (CPPA) suggested under Bill C-27 establishes separate categories of anonymized and de-identified data. Under the bill, to anonymize "means to irreversibly and permanently modify personal information, in accordance with generally accepted best practices, to ensure that no individual can be identified from the information, whether directly or indirectly, by any means," whereas to de-identify "means to modify personal information so that an individual cannot be directly identified from it, though a risk of the individual being identified remains" (House of Commons of Canada, 2022a). Bill C-27 kept de-identified data within the regulatory framework but excluded anonymized data, assuming that they cannot be re-identified (Dekker & Martin-Bariteau, 2022; House of Commons of Canada, 2022a). These separate data categories were introduced partially to offer organizations more flexibility in the processing of anonymized and de-identified information for "internal research, analysis and development purposes" (House of Commons of Canada, 2022a; Gratton *et al.*, 2023). Anonymized data are also exempt from retention limits, and the right of erasure does not apply to them (House of Commons of Canada, 2022a; Scassa, 2022).

Some researchers, however, criticized the proposal to exclude anonymized data from data protection rules, partly because quantum-enabled AI systems may be able to re-identify anonymized data, thereby exacerbating privacy risks (Dekker & Martin-Bariteau, 2022). The proposed *Artificial Intelligence and Data Act* (part of Bill C-27) aims to partially address this issue by imposing anonymized data governance requirements on private sector organizations, requiring them to "establish measures with respect to (a) the manner in which data is anonymized; and (b) the use or management of anonymized data" (House of Commons of Canada, 2022a). As of September 2023, Bill C-27 has not passed.

Quantum computing may undermine encryption as a defence against liability for data breaches

Another legal challenge for privacy in the quantum age is related to liability for data breaches. According to PIPEDA, any company falling under the scope of the statute must disclose privacy breaches to both the Office of the Privacy

Commissioner of Canada (OPC) and the affected individual when there is a "real risk of significant harm to an individual" (GC, 2000). To assess the real risk of significant harm, the OPC suggests organizations consider, among other things, the nature of the breach and whether the lost data were adequately encrypted or anonymized. This means that, in some instances, organizations may be able to mitigate liability for a data breach if they can demonstrate that data were encrypted (OPC, 2021). However, the risk of retroactive decryption of collected and stored data may undermine encryption as a defence against liability. While some data might be outdated by the time the first quantum computer can break today's encryption, other data, such as health records and social insurance numbers, will still be valuable to malicious actors.

5.2 Intellectual Property

Quantum computers and other quantum applications, such as sensing, cryptography, and communications, are eligible for IP protection (Kop, 2021b; Rand & Rand, 2022). IP rights encompass several rights regimes, including patents, copyright, and trade secrets. Generally, these regimes aim to promote innovation by granting the owners an exclusive right to make public, commercialize, reproduce, and limit distribution of their inventions (McKenna, 2006). IP rights are instrumental in building the quantum sector's value appropriation strategy because they can prevent, for a period of time, third parties from deriving economic benefits from the inventions or original expressions of IP owners (DOJ & FTC, 2007).

IP strategies deployed by large firms can stifle innovation and create obstacles for domestic quantum SMEs

Under Canada's *Patent Act*, a patent grants an inventor the "exclusive right, privilege and liberty of making, constructing," using, and selling an invention, which is defined as "any new and useful art, process, machine, manufacture or composition of matter" and "any new and useful improvement" thereof (GC, 1985d). For a patent to be granted, the invention must meet the requirement of novelty, be inventive (i.e., not obvious to a person possessing relevant skills), possess utility, and relate to patentable subject matter. The codified legal regime for patents is interpreted by a body of judicial decisions that, among other things, establish the requirements of patentability (Hagen *et al.*, 2022).

One of the key goals of the patent system is ensuring public disclosure of inventions (Hagen *et al.*, 2022). In *Teva Canada Ltd. v. Pfizer Canada Inc.*, the Supreme Court described the patent system as "a kind of a bargain:" in exchange for receiving a patent, the inventor must make the invention public (SCC, 2012). Despite the patent regime's goal of public disclosure, the use of a combination of

IP rights by large firms can undermine the goal of encouraging innovation and exacerbate social inequities. Kop (2020) notes that "strategically using a mixture of IP rights to maximize and protect the value of the IP portfolio of the quantum computer's owner, can result in an unlimited duration of global exclusive exploitation rights for first movers."

The exercise of IP rights by a dominant player can make a winner-takes-all scenario more likely. For example, Microsoft has used a topological structure to build a quantum computer while many of its competitors have relied on superconductors (Hoofnagle & Garfinkel, 2021). If its approach is more successful, Microsoft could protect the engineering aspects of topological structures by invoking trade secrecy and "by selling its quantum computers as a service rather than as standalone devices" (Hoofnagle & Garfinkel, 2021). While this strategy would allow the company to gain a competitive advantage, it could also impede the development of hybrid quantum processors that draw on the strengths of technologies developed by different IP owners.

Patents owned by larger firms can also discourage follow-on research, as well as product development and commercialization by SMEs, because "the cost of accessing those patents, through either royalties or legal battles, may simply be too high for small firms to sustain" (Gallini & Hollis, 2019). Dense webs "of overlapping intellectual property rights" that impede technology commercialization by SMEs (i.e., patent thickets) (Shapiro, 2000) can be found in two technology fields where Canadian innovators have historically enjoyed a relative advantage: computers and communications (Gallini & Hollis, 2019).

A lack of domestic IP retention strategies targeting publicly funded research has facilitated the market dominance of large foreign firms in Canada (Hinton *et al.*, 2023). The majority of patents generated by publicly funded Canadian universities land abroad, thereby reducing the ability of domestic firms "to commercialize [their] technology while contending with the IP and intangible asset positions of [their] competitors" (also known as Freedom to Operate) (Hinton & Witzel, 2023). The Canada Innovation Corporation Blueprint acknowledges this problem, noting that "without proper protections, powerful global multinational firms can challenge the ownership of intangible assets in order to complicate the commercialization of competitive technologies by Canadian companies" (GC, 2023a). Ultimately, in the absence of a domestic IP retention strategy, publicly funded research tends to generate economic benefits for foreign companies and countries, rather than for Canada.

IP ownership can create advantages for smaller firms

IP assets can stimulate the growth of SMEs in different stages of development (including start-ups and university spin-offs) (EPO, 2017). Compared to firms that lack IP rights, IP-holding SMEs are more likely to receive higher amounts of financing (since IP can be used as collateral for loans), innovate, realize plans for domestic and international expansion, and experience higher growth (Collette & Santilli, 2019). IP rights, and particularly patents, enable innovators to fend off competitors, protect their businesses from large firms, and build patent portfolios that facilitate cross-licensing agreements (Gallini & Hollis, 2019). In technology markets dominated by several large companies, SMEs that hold patents on parts of an innovative process can obtain significant licensing royalties (Galasso & Schankerman, 2018).

Lawmakers will face practical difficulties in codifying a *sui generis* patent regime for different applications of quantum technologies

The following parts of a quantum computer can be protected by patents:

> *the technology building blocks (qubits), quantum gates and multipliers, quantum integrated circuit chips, the various types of quantum processors such as … quantum interference devices, compiler engines (i.e., optimizers, translators, mappers), decoders, the simulator and the emulator, the circuit drawer, the microarchitecture …, the quantum-classical interface, the quantum instruction set architecture, and quantum memory.*
>
> Kop (2021a)

Computer-implemented inventions (e.g., programs, methods) (EPO, 2023) may also be patentable if they meet the physical existence requirement or manifest a discernible effect or change (CIPO, 2020). Therefore, the computing process is eligible for patent protection. Finally, quantum-enabling infrastructure, such as dilution refrigeration devices, can also be patentable if it meets the conditions of usefulness, novelty, and non-obviousness (Kop, 2021b).

A global landscape study that examined patent application and grant data from 2001 to 2021 suggests that the existing system is incentivizing public disclosure in quantum computing (Aboy *et al.*, 2022). Big technology companies, quantum SMEs, start-ups, universities, and the public sector are listed among the top initial patent assignees. There is a risk that tampering with the existing patent system could lead to negative results for innovation and adoption of quantum computing (Aboy *et al.*, 2022). Policy-makers will face practical difficulties in codifying a differentiated IP regime for different applications of quantum (Kop & Brongersma, 2021).

The increasing overlap between classical and quantum technologies raises a question about how to define a quantum technology patent and create a *sui generis* patent law regime for quantum technologies (Aboy *et al.*, 2022). Finally, the World Trade Organization *Agreement on Trade-Related Aspects of Intellectual Property Rights* (TRIPS) prohibits discrimination among technologies in patent law (WTO, n.d.).

Given the potential negative effects of patents on SMEs and innovation, monitoring will be an essential component of quantum IP policy. Proactive policy interventions are contingent upon empirical research, theoretical insights, and lessons learned from past developments. Effective interventions will also have to consider the interplay between IP protection and competition law (Kop *et al.*, 2022) (Section 5.3).

The object code that directs the functions of quantum computers presents challenges for copyright

Unlike patents, copyright arises automatically and protects original expressions of ideas, including those contained in software such as "computer source code, visual user interface elements, API [Application Programming Interface] structure, user documentation and product guides" (Bereskin & Parr LLP, n.d.). The functional aspects of software, however, are not subject to copyright protection (Samuelson, 2017).

Copyright can protect aspects of quantum technology that constitute "literary works" under the *Copyright Act* (GC, 1985e; Bereskin & Parr LLP, n.d.). For example, in some contexts, the following components of a quantum computer are eligible for copyright protection: "quantum software, the APIs, quantum arithmetic unit (quantum addition, subtraction, multiplication, and exponentiation), runtime assertion and configuration, quantum computing platforms, program paradigm and languages, the Bacon-Shor stabilization code, color codes, and surface codes" (Kop, 2021b).

These components are eligible for copyright if they meet the criterion of *fixation* (White, 2013; Dylan, 2019). A work is fixed when it is "expressed to some extent at least in some material form, capable of identification and having a more or less permanent endurance" (Exchequer Court, 1954; Hagen *et al.*, 2022). Fixation is one of the main requirements of copyright because it prevents people from claiming legal protection for thoughts (Schmit, 2013). However, according to Schmit (2013), the material form requirement could be problematic for quantum software because the quantum object code cannot be fixed for "more than a transitory duration due to superposition" that "allows a system of n-qubits to be any or all of 2^n different possibilities *simultaneously*" [original emphasis].

Trade secret protections are popular, but they do not protect inventions against reverse engineering

Studies that use patent applications and grant data to assess the anticompetitive effects of IP face limitations, because information about innovations protected by trade secrets is not publicly available and cannot be analyzed (Kop *et al.*, 2022). Start-ups in the software and hardware sectors frequently resort to trade secrets due to their lower cost and greater legal certainty (compared to copyright — which only protects the original expression of an idea — and patents) (Levine & Sichelman, 2019). Some successful start-ups that develop quantum sensors, computers, and communications systems rely on trade secret protections for hardware and software to make themselves more attractive for investors (Kop & Brongersma, 2021). Trade secrets, however, have disadvantages. They restrict knowledge flows and labour mobility, impede innovation, and create barriers to entry for competitors. They also do not protect inventions against reverse engineering (Gov. of U.K., 2021); contract clauses that ban reverse engineering limit but do not eliminate this risk (Kop, 2021b).

5.3 Competition Law

Competition law prohibits refusals to deal, monopolization, cartels, price fixing, and other business practices that can harm the market and consumers (Kop & Brongersma, 2021). In Canada, the *Competition Act* ensures, among other things, “that small and medium-sized enterprises have an equitable opportunity to participate in the Canadian economy and in order to provide consumers with competitive prices and product choices" (GC, 1985b). In accordance with the *Competition Act*, some anticompetitive behaviour (e.g., horizontal collusion in the form of cartels) is a criminal offence, and proof of competitive harm is not required to establish it. Other forms of anticompetitive behaviour (e.g., abuse of a dominant position, restrictive trade practices) are considered less dangerous and are subject to different remedies, such as fines and cease-and-desist orders (GC, 1985b).

The application and enforcement of competition law may favour major market players

Forming and fragmented markets, such as those for quantum technologies, rarely display signs of anticompetitive behaviour that could trigger regulatory intervention (Kop & Brongersma, 2021). Moreover, competition law is not designed to prevent the winner-takes-all effects resulting from the exercise of various IP rights. On the contrary, the application of competition law can encourage legal market dominance and favour major market players with a portfolio of quantum IP rights, as long as they wield their market power in a legal way (Dekker &

Martin-Bariteau, 2022). However, protections granted by IP rights are not absolute; in some cases, competition authorities and courts can prohibit certain conduct by IP owners because it contravenes competition law (Anderman, 2007; Kop *et al.*, 2022).

The *Competition Act* was amended to enable more effective enforcement in the digital economy

The emergence of digital markets dominated by global technology firms prompted calls to amend competition laws in Canada, in order to deter the improper concentration and leveraging of market power. Amendments to the *Competition Act* passed in 2022 aim to improve enforcement in the digital economy (GC, 2022a). Specifically, the abuse of dominance provisions were amended to expand the definition of *anticompetitive act* (GC, 1985b). Whereas that definition previously focused on conduct having a "predatory, exclusionary or disciplinary impact on a competitor," its amended version considers conduct "*intended* to have a predatory, exclusionary or disciplinary negative effect on a competitor, or to have an adverse effect on *competition*" (GC, 1985b). This amendment capturing acts *intended* to cause broader competitive harm is particularly important in the context of digital markets, where big technology companies may abuse their dominant position by acquiring a number of up-and-coming quantum firms. If it becomes apparent to the Competition Bureau that a dominant firm adopted a strategy of acquiring nascent competitors, the practice of such acquisitions could amount to an adverse effect on competition under the *Competition Act* (Iacobucci, 2021).

Further amendments to the *Competition Act* and boosting enforcement powers could help redress economic harms arising from market dominance

The *Competition Act* could be further amended to prevent dominant technology companies from acquiring nascent competitors before they can gain a competitively meaningful market share. The act requires that the Competition Bureau assess only "quantifiable" anticompetitive effects of a merger, if the merging parties invoke the efficiencies defence (GC, 1985b). This requirement focuses on the price effects of mergers. According to Iacobucci (2021), econometricians can in principle quantify any effect, including "the economic impact of a chilling effect on innovation." An amendment to the act could remove the requirement to rely on quantitative evidence when establishing whether a merger may considerably reduce or prevent competition. In addition, the Competition Bureau could pay closer attention to the influence of mergers that not only lessen but also prevent competition, particularly in the context of acquisition of up-and-coming firms. Further amendments to the *Competition Act* could be introduced to clarify that the Competition Tribunal is empowered to make orders where anticompetitive conduct may stifle innovation (Iacobucci, 2021).

5.4 Standards and Standardization

Information technology standards can be defined as "written specifications dictating how to develop software and hardware to be compatible with any other type of software and hardware that also adheres to these specifications" (DeNardis, 2013). Standardization is a lengthy process that includes the work of specialized committees, the publication of standards by authorized organizations, national recognition of standards, the application of standards by the private sector, conformity assessments, and the accreditation of conformity assessment organizations (Standards Council of Canada, 2021). Standardization is a key instrument of innovation policy because it can protect consumer safety and remove international trade barriers, facilitating international adoption of quantum technologies created in Canada (Girard, 2019; Kop, 2020). In addition, technical standards play an important role in shaping public policy on technology accessibility, individual rights, and security. Policy implications of standards raise questions about how standards are procedurally established and by whom (DeNardis, 2013), and what role Canada plays in shaping standards for quantum technologies to ensure they promote individual and collective human rights.

Quantum technology standards are fragmented

The ongoing work on quantum technology standards is distributed across multiple institutions often doing similar work (DeNardis, 2022). The emergence of new technologies leads to tensions in standards-setting between legacy organizations with expertise in ICTs (but not necessarily quantum) and ad hoc standards-setting industry groups with expertise in quantum (but not other ICTs). Several organizations and forums have started working on quantum-resistant cryptography (QRC), quantum information network standardization, and, more specifically, anticipated quantum computing threats to public-key cryptography (Table 5.1) (Section 2.1.3). Some of these efforts are geared toward the proprietary specifications of certain companies, which may lead to these companies acquiring market advantage over their competitors (DeNardis, 2022).

Table 5.1 A Snapshot of Quantum Standardization Efforts

Standards Development Organization	Select Deliverable Topics	Type of Output
The relevant work of the *European Telecommunications Standards Institute (ETSI)* takes place in the Technical Committee on Cyber Security (CYBER) and the Industry Specification Group (ISG) on quantum key distribution (QKD).	QKD: authentication, components, and internal interfaces; architectures and frameworks; vocabulary; case studies; optical characterization Quantum computing impact of ICT systems Quantum-safe cryptography	Informative: group reports, technical reports, white papers, ETSI guides Normative: technical and group specifications
The *Institute of Electrical and Electronics Engineers (IEEE)* is a U.S.-based professional association that has established standards for consumer electronics, computers, and telecommunications.	Software-defined quantum communication Quantum technologies definitions Quantum computing performance metrics and benchmarking	Normative: standards
The Internet Research Task Force (IRTF) focuses on longer-term research issues related to the internet, while the parallel organization, the *Internet Engineering Task Force (IETF)*, focuses on the shorter-term issues of engineering and standards-making.	Applications, use cases, and architectural principles for quantum internet Transition to QRC	Informative: informational documents Normative: Proposed standards
The *International Organization for Standardization (ISO) / International Electrotechnical Commission (IEC) / Joint Technical Committee (JTC)* has 2 entities developing quantum technology standards: Working Group (WG) 14 Quantum computing and Sub-committee (SC) 27 Information security, which specifically addresses QKD security.	Terminology Security requirements; testing and evaluation methods for QKD	Normative: international standards
The Study Groups (SG) of the *International Telecommunication Union's Telecommunication Standardization Sector (ITU-T)* assemble global experts to develop international standards known as ITU-T Recommendations. SG11 (Signalling Requirements), SG13 (Future Networks), SG15 (Transport, Access and Home), and SG17 (Security) are in the process of developing documents of interest for the quantum sector.	Security, management, and architecture of QKD networks	Normative: Recommendations Normative: international standards

Adapted from: ITU (2021)

The Chinese government is also working on developing standards for quantum technologies. In 2021, it announced the National Standardization Development Program (NSDP), which provides that standards-setting is a national priority and establishes country-wide guidance on how the public sector, researchers, and individuals should incorporate standards-setting into their work (Frantz, 2022). According to the NSDP, researchers and scientists will be required to allocate portions of their projects to standards-setting. The focus of the strategy is on domestic standards-setting; it remains to be seen to what extent these standards will be aligned with international quantum technologies standards developed by various organizations (Frantz, 2022). SAC/TC578 — China's group tasked with developing these standards — began working on basic quantum computing terminology and definitions in 2020 (CIRA, 2022).

At the initial stages of technology development, fragmentation of standards can be explained by the need to rapidly design new products, rather than focus on interoperability (DeNardis, 2022). The International Telecommunication Union's (ITU) quantum study group warns, however, that "these candidate standards may overlap and conflict, preventing any single standard from being broadly adopted and forcing companies to bear the financial burden of making their products compatible with multiple standards" (ITU, 2021). Once working products and standards materialize, harmonization — potentially incentivized by government security or procurement policies — can remedy fragmentation challenges and ensure innovation (DeNardis, 2022).

Standardization, however, does not have the same legal effects as laws and regulations. As mentioned in Section 5.1, data protection and privacy laws that rely on encryption as a requirement to prevent data breaches or limit liability do not account for quantum computing. In this respect, standards will prove effective in ensuring the security of digital infrastructure and private communications if they are incorporated into laws and regulations, and enforced by the administrative state (Girard, 2019; Bruno & Spano, 2021). Canada is taking steps in this direction; some commentators believe, however, that legislative proposals confer too much discretion on regulators (CCLA, 2022; Parsons, 2022), increasing the risk of regulatory capture (Section 5.6).

The dominance of select countries in the standards-setting process could negatively affect Canadian quantum producers and end-users

Despite the participation of experts from Canada in international standardization bodies (Standards Council of Canada, 2021), the experience of developing international AI standards shows that major market players (e.g., China, United States, European Union) could export their domestic regulations and rules into international standards to create or entrench a first-mover advantage (SRI, 2023). The dominance of select countries in the standards-setting process could lead to fragmentation of standards, thus affecting technology interoperability, international trade, and, ultimately, diffusion and adoption (SRI, 2023).

While some international standards could be adapted to a Canadian context, ensuring meaningful Canadian participation in standards-setting processes for quantum technologies could translate into leadership in the development of international conformity assessment schemes and accreditation programs that support international trade (SRI, 2023). In the panel's view, given the small size of the domestic market, influencing international standards and securing access to international markets is necessary to ensure broad adoption of quantum technologies produced in Canada (Chapter 6).

5.5 Domestic and Foreign Trade Regulations on Dual-Use Technology and Infrastructure

Dual-use technologies are designed for commercial or civil use but could also be used for military purposes (TCS, 2021a). Export controls on dual-use technologies are established through special lists that countries implement voluntarily in accordance with the 1995 *Wassenaar Arrangement* (WAS, 2021). As of 2022, 42 states, including Canada and its international allies (e.g., Australia, New Zealand, United Kingdom, United States, European Union) are following this arrangement (WAS, 2022). Some quantum technologies are listed in the *Wassenaar Arrangement*, including gravimeters, QRC, and some superconducting quantum interference devices (SQUIDs) (WAS, 2021). The document also mentions predecessors to quantum encryption, sensing, and computing, in order to prevent their export to some jurisdictions.

5.5.1 Domestic Export and Import Control Regulations

The *Export and Import Permits Act* (EIPA) gives the Governor in Council (GIC) the power to restrict the export of certain goods from Canada (GC, 1985a). Since 2004, EIPA rules extend to technology transfers, including "technical data, technical assistance and information necessary for the development, production or use of an article included in an Export Control List". Quantum technologies listed in the *Wassenaar Arrangement* are included in the *Export Control List's* dual-use category, meaning that their export requires a permit. The EIPA provides for administrative discretion in Canada's export permit process. The Government of Canada can include an article on the list if it determines that it can be used to jeopardize national security, undermine the sovereignty of Canada, endanger the safety of people in Canada, disturb the provision of essential services, or harm a foreign country or region of the world (GC, 1985a).

Canada's international trade obligations do not prohibit the establishment of additional controls and safeguards on quantum technologies. Article XXI of the 1947 *General Agreement on Tariffs and Trade* provides that countries may introduce exceptions to trade rules to protect "essential security interests" (WTO, 1947). While the precise meaning of "essential security interests" is ambiguous, the risks presented by quantum technologies — particularly their potential to destabilize domestic infrastructure or intelligence and military capabilities — may be similar to some other regulated technologies that qualify for trade exceptions (Forcese & West, 2021; Dekker & Martin-Bariteau, 2022).

Relatively few Canadian firms export their goods; among those that do, the vast majority export solely to the United States. In 2017, only 12% of domestic SMEs exported and, in 2018, Canada ranked 32nd in the world for high-tech exports (Asselin & Speer, 2019). As such, additional export controls may present burdens for domestic firms willing to participate in international trade and sell technology for safe and legitimate purposes. By reducing the potential market size for technology diffusion, regulations and trade restrictions also make companies less attractive for investors. In the long term, export controls can be ineffective because they stimulate the development of autonomous foreign technology networks resistant to any restrictions (Hoofnagle & Garfinkel, 2021).

5.5.2 Foreign Export and Import Control Regulations

Placing export controls on materials and technology is an important instrument for countries that wish to maintain domestic innovation advantage. Some countries, including Canada's allies, are leaning toward a restrictive approach to quantum technologies, materials, and equipment.

Foreign regulations on infrastructure and materials can disrupt supply chains and negatively affect quantum producers and end-users in Canada

Canadian companies and research centres depend on foreign resources to perform their work (Section 3.3.1). This reliance on international supply chains poses geopolitical risks, as countries that supply infrastructure and materials could enact export control regulations that have spillover effects on Canadian companies, researchers, and end-users (INDU, 2022b) (Box 5.4).

Box 5.4 Export Controls on Dilution Refrigerators

The acquisition of dilution refrigerators is one area where export control regulations may materialize. It can take many months for a company to procure a specialized dilution refrigerator that can cost between $500,000 and $1 million and is custom-made by only a handful of companies (Giles, 2019). The cooling systems of dilution refrigerators rely on a combination of gases for supercooling. One of these gases is Helium-3, an isotope of helium that is available in quantity only on the moon (Bilder, 2009). On Earth, it is usually a by-product of government programs on nuclear research and weapons, which restricts its availability (Giles, 2019).

Canada's major trade partners, the European Union and the United States, include Helium-3 and Helium-3 refrigerators in their lists of dual-use items, meaning that authorities may deny the export of such items to certain legitimate buyers in business and research communities (E.C., 2020; GAC, 2020; Kaartosalmi, 2021). Although export controls do not apply to Helium-3 refrigerators used for quantum computing, the same refrigerators are used in tritium facilities and plants. Export control authorities can exercise discretion in imposing bans, which creates uncertainty and bureaucratic burdens for the producers and end-users of dilution refrigerators (Kaartosalmi, 2021).

Moreover, the use of cryogenic dilution refrigerators for quantum computing prompted discussions about placing them on export control lists (Hoofnagle & Garfinkel, 2021). Both the European Union and the United States have considered labelling them as dual-use equipment. For example, the U.S. Department of Commerce's Bureau of Industry and Security (BIS) has been considering placing quantum dilution refrigerators on the list of controlled emerging technologies under the *Export Control Reform Act of 2018*; however, no final decision has been made (Gov. of U.S., 2018; Hoofnagle & Garfinkel, 2021; Torres Trade Law, 2022).

The U.S. has considered additional export controls on quantum technologies

In addition to placing controls on materials and equipment, some countries may consider limiting the export of quantum technologies themselves. This may present significant challenges for users in Canada, particularly if such technologies provide social, economic, or military benefits and are not produced domestically. In 2018, the U.S. Department of Commerce's Bureau of Industry and Security (BIS) issued an advance notice of proposed rulemaking to solicit feedback on export controls for a number of technologies under the *Export Control Reform Act of 2018* (BIS, 2018). Quantum information and sensing technologies were specifically identified as "emerging and foundational technologies" for export controls "because they have potential conventional weapons, intelligence collection, weapons of mass destruction, or terrorist applications or could provide the United States with a qualitative military or intelligence advantage" (BIS, 2018). In 2019, the BIS placed controls on quantum resistant cryptographic algorithms (BIS, 2019), but has not issued orders on other quantum technologies not included in the *Wassenaar Arrangement* (Torres Trade Law, 2022).[13]

Some research suggests, however, that "imposing further export controls on quantum computing and communications technology would slow scientific progress, and given the early stage of the technology, export controls cannot yet be applied in a way that is targeted to defense-relevant applications" (Parker *et al.*, 2022). This view contradicts more optimistic assessments of the maturity and commercialization of quantum technologies for defence purposes (e.g., quantum radar for stealth craft detection, gravitational and magnetic sensors for measurement and signal intelligence) (Hoofnagle & Garfinkel, 2021). If the latter view prevails, restrictive export control regulations will follow. At the same time, U.S. export controls are not absolute and may not apply to vetted U.S. trade partners and research collaborations (Dekker & Martin-Bariteau, 2022). As an example, Canada and the United States are ramping up co-operation in the semiconductor market. These emerging partnerships solidify Canada's role in semiconductor supply chains and mitigate the risks of supply chain disruptions for domestic technology producers and users (Box 5.5).

In 2022, the Government of Canada published its Indo-Pacific Strategy, which aims, among other things, to "expand trade, investment and supply chain resilience" (GC, 2022e). Although the strategy does not specifically mention quantum technologies, it includes several programs and co-operation areas (e.g., export and trade missions, information security, technology interoperability and standardization) that could minimize the risk of supply chain disruptions and support the commercialization and international adoption of quantum technologies produced in Canada.

13 The United States has imposed additional export restrictions against some countries and entities (Reisinge & Salamatin, 2022).

Box 5.5 Canada-U.S. Co-operation in the Area of Semiconductors

In August 2022, U.S. Congress passed the *Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act*, which allocated US$280 billion toward strengthening the semiconductor industry. These developments present opportunities for the Canadian public and private sectors. The Government of Canada can build on its trade agreements with the United States and co-operate with the private sector to acquire semiconductors directly from U.S. producers, thereby reducing the risk of supply chain disruptions (Budning *et al.*, 2023). As noted in Section 3.1.3, the Government of Canada signed an MOU with IBM in 2023 to expand domestic R&D and the manufacturing of semiconductors in Quebec through a cross-border manufacturing corridor (GC, 2023c).

The E.U. supports public access to quantum technologies

The E.U. approach to quantum technologies promotes openness and focuses on human-centric and anti-surveillance applications. Its €1 billion initiative to support quantum technologies calls for "end-user-inspired applications in quantum networks and ... quantum random-number-generation-based encryption in 'cheap devices'" (Hoofnagle & Garfinkel, 2021). This posture suggests the European Union may have long-term plans to support a broadly available end-to-end quantum internet. The anti-surveillance and human-centric orientation of the E.U. quantum adoption strategy is aligned with several E.U. court opinions that aim to protect residents from intelligence gathering by U.S. agencies (Hoofnagle & Garfinkel, 2021).

The European Commission acknowledges that premature and fear-driven export-control regulations can stifle the growth of certain quantum technology sectors altogether (E.C., 2022). For this reason, the European Union plans to engage in consultations with international allies — notably the United States — on developing common approaches for the quantum industry, hoping this will ensure the growth of the quantum industry in Europe (E.C., 2022). It remains to be seen whether the European Union will be following a more restrictive approach to quantum technologies, similar to that considered by the United States. The U.S.–E.U. Joint Statement of the Trade and Technology Council, released in 2022, does not mention the coordination of national quantum policies as an objective (TTC, 2022). Coordination efforts occur within the *Wassenaar Arrangement*, standardization committees, and sanction regimes implemented against certain countries.

5.6 Regulatory Uncertainty and the Risk of Regulatory Capture

Regulatory uncertainty refers to "uncertainty about the overall regulatory environment, which could be driven by a broad range of regulation-related events such as the promulgation of a new regulation, a company's regulatory compliance or violation, a regulatory investigation, or a lawsuit challenging agency regulatory action" (Xie, 2022). Some scholars argue that uncertainty about externalities, including regulations, postpones investments in technology adoption to a time of reduced investment risks and greater certainty (Yang *et al.*, 2004; Frederiks *et al.*, 2022). This is particularly true when organizations expect to receive clearer guidance from regulators in the short- or mid-term. (Hoffmann *et al.*, 2009).

Regulatory uncertainty could impede the adoption of quantum technologies by potential end-users

The negative effects of regulatory uncertainty on technology development, diffusion, and adoption by end-users can be illustrated with a few examples. In Canada, regulatory uncertainty surrounding factory assembly and licensing processes for small modular reactors has been identified as an obstacle to the wide commercialization of this technology (Twyman *et al.*, 2021). In the European Union, the lack of legal clarity regarding genome editing classification in E.U. crops undermined confidence in the technology (Jones, 2015). In the United States, regulatory uncertainty weakened investments in renewable energy and energy storage technologies (Outka, 2012; Stein, 2014). In 2021, Google published the results of an international survey on cloud adoption, conducted among 1,363 senior financial industry executives in Australia, Canada, France, Germany, Hong Kong, Indonesia, Japan, Singapore, the United Kingdom, and the United States; 84% of respondents believed regulatory reviews and approvals were too time-consuming, and 78% identified regulatory uncertainty over the use of the public cloud as an obstacle to broader adoption of this technology (Maufe, 2021).

Regulations may create favourable conditions for select market players

Regulatory capture occurs when different interest groups influence the policy-making process to the detriment of the broader public interest (Helm, 2006). The involvement of select industry players in the regulatory process may weaken health and safety standards, stifle competition and innovation, and minimize the importance of alternative sources of evidence and knowledge (Woodhouse, 2005).

One of the reasons for regulatory capture — a lack of subject-matter expertise among policy-makers — may be relevant for quantum technologies (McCarty, 2013). According to a study conducted for the Government of Canada in 2020, policy-makers lack knowledge and awareness of the opportunities and risks presented by quantum technologies (Doyletech Corporation, 2020). In part, this may be because government agencies are experiencing challenges in their efforts to recruit and retain quantum specialists. For example, in the United States, high industry salaries, slow government hiring processes, and misconceptions about government work were identified as the main factors keeping professionals from considering government careers in quantum information science (NQCO, 2022).

Private expertise coupled with significant resources in that sector can exacerbate a power imbalance between the quantum industry and policy-makers (WEF, 2022b). International standards-setting is one regulatory area where large companies have been successful at advancing their own interests (Büthe & Mattli, 2014). For example, the ISO adopted Microsoft's "open XML" as an international standard, thereby improving the firm's chances of accessing profitable government contracts. This decision prevented Microsoft's competitors from proposing an alternative option for document compatibility across multiple platforms (Büthe & Mattli, 2014).

In addition, the accumulation of knowledge and resources in the hands of a few actors could have negative geopolitical implications, worsening disparities among different countries and regions of the world (WEF, 2022b). In the panel's view, there is a greater risk of regulatory capture when government policy focuses on stimulating quantum technology production and pays less attention to the needs of technology end-users.

6

Enabling Conditions for Adoption

Chapter Findings

- Conditions enabling the *production* of quantum technologies do not guarantee their *adoption* by end-users.
- The Government of Canada has been slow to implement policy instruments to stimulate the demand for innovation, focusing instead on supply-side instruments. The adoption of quantum technologies by the public and private sectors requires policies and instruments intended to encourage the demand for innovative quantum products.
- The adoption of quantum technologies relies on a number of enabling strategies, including public-private co-operation (e.g., government procurement, partnerships, advisory boards), pro-competition market oversight and regulatory intervention, industry-led initiatives (e.g., professional services, regional hubs, industry consortia), and building a quantum workforce for the adopting sectors.
- Reforms will likely be needed to develop a quantum-ready workforce, including skills development programs that focus on transferring expertise from quantum information science to quantum technology development, as well as industry-academic coordination and collaboration, and adoption-side training.

Canada is home to a number of research hubs and SMEs that focus on creating, designing, and producing quantum technologies. Public policies that stimulate domestic technology production are beneficial for several reasons, including securing domestic supply chains, training a quantum workforce, and laying a foundation for future partnerships for technology diffusion. However, quantum technology production does not automatically translate into adoption by end-users. Creating the enabling conditions to drive the domestic adoption of these technologies requires coordinated and deliberate actions by different orders of government, as well as academia and the private sector. This chapter reviews several levers that may encourage adoption, including public-private co-operation, pro-competition market oversight, regulatory interventions in select sectors, and industry-led professional support services and consortia. In addition, it explores the role of education, training, and immigration in developing a quantum-ready workforce for the adopting sectors.

6.1 Public-Private Co-operation

Overcoming the technical, institutional, social, ethical, legal, regulatory, and economic challenges impeding the adoption of quantum technologies will require a coordinated, collaborative effort. This could take a variety of forms, including procurement and government programs designed to support innovation in the quantum sector, triple helix-style public-private partnerships (PPPs), sectoral councils and government advisory boards that serve as an interface between government and industry, and collaborative roadmapping processes that bring together a wide range of stakeholders to develop strategic plans.

6.1.1 Boosting Adoption Through Government Procurement and Other Programs

As noted in Chapter 4, Canada's innovation policy has historically prioritized the supply side of the innovation process (such as investments in research), while underutilizing strategies for technology diffusion and adoption. In part, demand-side innovation policies may be needed because quantum technologies are competing with classical ones, which in many cases are sufficient to meet business needs and are cheaper and more familiar than quantum technologies. Policies that stimulate demand for quantum technologies may be required for end-users to even consider experimenting with new solutions.

There are opportunities to increase the role of government procurement to boost adoption

There are opportunities to increase the role of procurement, particularly by Innovative Solutions Canada (ISC), in quantum technology adoption in the public sector. This is aligned with the goals of the *National Quantum Strategy* (NQS), which has allocated a small amount — $35 million over seven years — to ISC to support the commercialization of quantum technologies (ISED, 2023d). ISC has two streams: Challenge and Testing (ISED, 2019b). In 2022, ISED launched the Pathway to Commercialization program for quantum technologies under the Testing stream (ISED, 2022e) (Box 6.1). However, the Challenge stream, which is focused on R&D "to solve internal departmental operational issues and/or to fill a gap in the marketplace" (ISED, 2023c), may be better adapted than the Testing stream for the low technology readiness levels of many quantum technologies. The Challenge stream provides quantum SMEs with an opportunity to co-develop solutions with end-users in the public sector.

Box 6.1 Pathway to Commercialization Testing Stream

The Pathway to Commercialization program under ISC's Testing stream offers eligible SMEs the opportunity to compete for government contracts, contingent upon "the successful testing and market-readiness" of their prototypes (GC, 2021a). Successful applicants receive an initial ISC testing contract, after which they may be put on a Pathway to Commercialization list; government buyers can purchase successfully tested innovations from the list with applications in such sectors as "defence, energy, pharmaceutical, chemical, advanced industries (automotive, aerospace, electronics, superconductors), finance, or transport and logistics" (Hemmadi, 2022; ISED, 2022e).

Technology diffusion strategies propelled by the proposed Canada Innovation Corporation (CIC) could enable adoption

Budget 2022 proposed establishing the CIC, committing approximately $1 billion over five years to support the corporation's mandate (GC, 2022d) (Box 6.2).

Box 6.2 Canada Innovation Corporation's Proposed Mandate and Functions

The CIC's proposed mandate is to provide funding and advisory services to encourage Canadian firms to launch and expand R&D activities, develop intangible assets (including IP), and retain them in Canada. The CIC will deliver the following services:

1. Financial support (i.e., grants, contributions) to encourage R&D activities across various economic sectors and at different innovation stages.
2. Program impact assessments to monitor changing private sector requirements, trends in the Canadian research ecosystem, and domestic and global technology developments.
3. Advisory services (e.g., providing information to firms on government funding opportunities) to help them prepare R&D proposals, connect businesses with researchers and R&D services, create links among firms across different sectors, and support "the creation and retention of intangible assets."

(GC, 2023)

The CIC's proposed mandate is modelled on Business Finland (formerly Tekes) and the Israel Innovation Authority (IIA) (GC, 2022d). However, establishing an innovation agency that invests in or creates new technology, including quantum, does not necessarily foster technology diffusion and adoption. For example, despite the IIA's ability to swiftly respond to funding applications, it has historically focused on *producing* new technology, rather than *diffusing* it (Breznitz *et al.*, 2018). Business Finland has achieved greater success at technology diffusion than IIA because it was established with this goal in mind; as part of its mandate, it can bring companies together to ensure the spread of technology across economic sectors.

In the panel's view, replicating the Finnish model in Canada will accelerate technology diffusion and adoption only if the specific parts of the model, such as inter-firm consortia and the integration of advanced users, are adapted to the domestic context. In Finland, a long history of price-fixing cartels and marketing consortia, among other factors, made it easier to engage firms as a group in innovation projects (Ornston, 2012). It is unclear whether Business Finland's conditions for success can be replicated in Canada due to the fragmentation of Canadian industry.

Patent collectives form one of the pillars of Canada's Intellectual Property Strategy. The goals of patent collectives are "to help SMEs operating in a dynamic technological area grow to scale by supporting their patent and other IP needs [and to] provide the Government with valuable insight into the IP issues faced by SMEs" (ISED, 2019a). The first federally funded patent collective was created to address the IP needs of Canadian SMEs operating in the clean technology sector (IAC, 2023). A similar patent collective could be established for quantum SMEs.

The Industrial Research Assistance Program (IRAP) could facilitate adoption due to its strong links to industry

The NQS identifies IRAP as a source of support for the commercialization of quantum technologies by domestic SMEs (ISED, 2023d) (Box 6.3).

Box 6.3 The Industrial Research Assistance Program (IRAP)

IRAP offers financial support, consulting services, and access to business networks for Canadian SMEs looking to commercialize their technology. It employs over 260 field staff across Canada and offers services aligned with particular business requirements. Twenty-nine percent of IRAP's clients are from the ICT or digital economy sector, which represents the largest sectoral concentration.

IRAP primarily connects with SMEs through its advisory services. IRAP's industrial technology advisors (ITAs) provide business and technical guidance, as well as referrals to scientific and business expertise among participating firms. Eligible firms participate in three primary funding streams: regular (supporting clients with awards between $50,000 and $1 million); the accelerated review process (for small projects below $50,000); and large-value contributions (i.e., $1 million, up to $10 million). Budget 2021 proposed $500 million over five years to expand IRAP funding; this amount is in addition to the $700 million committed in Budget 2018. Between 2018 and 2022, IRAP disbursed more than $1.3 billion to eligible firms.

(NRC, 2022c)

In 2023, the Government of Canada announced that IRAP will join the CIC and provide a foundation for delivering on its technology adoption mandate (GC, 2023a). IRAP has been described as a "productivity facilitator" program, meaning that it "introduce[s] small-scale, incremental product and process innovations across a wide range of established industries" (Breznitz *et al.*, 2018). It maintains close connections with the private sector, which allows it to facilitate the development of technological solutions that are responsive to immediate business challenges (Breznitz *et al.*, 2018). IRAP also offers clients IP advice about their technology commercialization strategies (NRC, 2023). In the panel's view, IRAP is well positioned to facilitate quantum adoption by end-users by virtue of its strong links to industry. However, it is unclear whether IRAP staff have relevant knowledge of Canada's quantum sector and potential end-users.

There are opportunities to enhance IRAP's technology commercialization support services

According to the NRC's internal review of IRAP, both clients and staff perceive it as supporting firms in the early stages of R&D (NRC, 2022c). Some clients noted the program could enhance services (including better access to business networks) for SMEs wishing to accelerate their prototypes to commercialization timelines. The respondents noted that IRAP could encourage its ITAs to connect with trade services, to improve the long-term development of SMEs. Some foreign organizations with mandates similar to IRAP's are offering these services. For example, Business Finland participates in Team Finland's[14] advisory services to provide clients with guidance on market entry strategies. Business Finland also supports technology commercialization through its TUTL and Innovation Scout programs (Valtakari *et al.*, 2018). Sweden's Vinnova offers financial support and information to clients, then connects them with Business Sweden, an export and investment council that helps domestic companies at the commercialization phase increase global sales (NRC, 2022c; Business Sweden, n.d.-a, n.d.-b).

6.1.2 Public-Private Partnerships and Triple-Helix Arrangements

Several foreign jurisdictions have developed some form of public-private partnerships (PPPs) aimed at accelerating the adoption of quantum technologies. Importantly, however, these arrangements are not PPPs as they are traditionally understood in Canada, which involve a contractual relationship between a government entity and the private sector to build infrastructure or deliver services (PSPC, 2022; CCPPP, n.d.); these have been subject to criticism (Siemiatycki, 2015). Rather, they are arrangements that typically establish hybrid organizations consisting of public and private sector entities, including governments, businesses, universities, and other research organizations.

These hybrid organizations may be best understood in terms of the *triple-helix* model of innovation. Under this model, cross-sectoral collaborations among industry, government, and academia — the three "strands" of the triple helix — can facilitate technology diffusion and adoption through the establishment of hybrid organizations at the intersections of these sectors (Etzkowitz, 2008). In these types of arrangements, boundaries between sectors become blurred as each takes on some of the traditional roles of the other two. For example, universities engage in technology transfer and become incubators for new start-ups, while technology developers in industry take on a training and education role that traditionally belongs to universities. Moreover, triple helix-based PPPs not only help drive technology adoption but also help synchronize "norms, standards, principles and values" across stakeholders by raising "awareness of its ethical, legal and social aspects" (Kop, 2020) (Chapters 4 and 5).

14 Team Finland is a network of business development entities (Team Finland, n.d.).

Several PPP-based hybrid organizations facilitating quantum technology adoption have been established in foreign jurisdictions, such as Germany's QuaST initiative and Quantum Delta NL's innovation hubs in the Netherlands (Box 6.4). Canada has established research hubs for biomanufacturing and life sciences (GC, 2023b) that are somewhat similar to the quantum hubs established in the Netherlands; these could be models for Canada's approach to quantum technologies.

Box 6.4 QuaST and Quantum Delta NL Innovation Hubs

In 2022, Germany launched a new project called QuaST (Quantum-Enabling Services and Tools for Industrial Applications) that aims to provide easy access to quantum computing for companies that have minimal knowledge of the subject and lack the resources and expertise to explore it on their own (Mathas, 2022; Fraunhofer IKS, 2023). QuaST supplies users with high-level libraries and development tools to address optimization problems in their business using hybrid classical-quantum algorithms. These components will eventually be licensed or integrated into open-source software tools (Mathas, 2022; Fraunhofer IKS, 2023). QuaST's approach is modelled on similar approaches to AI and has been successfully integrated into many businesses due in part to the widespread availability of software libraries and development tools (Fraunhofer IKS, 2023). In addition, QuaST offers training and seminars that help users explore and adopt quantum computing.

Funding for the project comes from the Federal Ministry for Economic Affairs and Climate Action of Germany and is overseen by the Fraunhofer Institute for Cognitive Systems IKS. Additional project partners include other Fraunhofer institutes, the Leibniz Supercomputing Centre, the Technical University of Munich, and several private sector companies (Mathas, 2022; Fraunhofer IKS, 2023). Early applications include semiconductor production and logistics, as well as optimizing business processes, networks, and supply chains; there are plans to explore use cases in pharmaceutical, automotive, and other safety-critical industries (Mathas, 2022; Fraunhofer IKS, 2023).

Quantum Delta NL is a Dutch PPP consisting of technology companies, government agencies, universities, and quantum research organizations. It works to accelerate the development of the Netherlands' quantum ecosystem. A central part of its strategy has been the establishment of

(Continues)

(Continued)

five innovation hubs across the country, specialized in particular areas of quantum technologies. Each hub is itself a PPP among different research institutions, universities, established firms, and start-ups (QDNL, 2019):

Delft: quantum computing, quantum internet, networking

Amsterdam: quantum software, quantum sensing, quantum simulation

Leiden: applied quantum algorithms, quantum and society

Eindhoven: quantum simulation, hybrid quantum computing, QRC, quantum protocols, quantum nanophotonics, quantum materials

Twente: quantum nanotechnology, quantum electronics, quantum photonics

The German approach may be better than the Canadian approach at driving adoption

Germany's QuaST project is focused entirely on driving the *adoption* of quantum technologies by non-quantum firms. By comparison, Canada's approach has been largely focused on quantum technology *development* and *production*. While such an innovation strategy may help Canada become a leader in quantum technology production, it does not guarantee that Canadian firms will invest in adoption. Perhaps the closest analogue to Germany's QuaST program in Canada is IBM's quantum hub at Université de Sherbrooke, which facilitates collaboration among university researchers, private sector companies, and governments (Sections 3.1.3 and 6.3.2). However, it is not specifically designed to drive adoption of quantum technologies.

PPPs may help accelerate adoption by identifying applications in relevant sectors

As noted in Chapter 2, the timeline and outlook for commercial adoption of quantum technologies depends on the identification of practical, near-term applications and use cases in specific sectors or industries. In 2022, the Quantum Economic Development Consortium (QED-C) undertook a study of existing PPPs in areas of technology application outside of quantum technologies, in order to identify lessons and best practices regarding "how technology application can be accelerated through public-private partnerships" (QED-C, 2022c). Following this review, they ultimately recommended that:

> *the most effective way to identify a set of potential near-term QC applications of value to government is through a discovery process that involves cooperation among all stakeholders, from quantum scientists to domain subject matter experts to end users to regulators.*
>
> QED-C (2022b)

In addition, QED-C noted that it is important this discovery process be focused on one particular area or sector where there is already significant interest in, and progress on, incorporating quantum technologies. If multiple areas or sectors are to be explored, separate discovery processes will be needed. The objective of these processes should be to undertake in-depth evaluations of potential applications in the focus area or sector, in order to identify strategies to accelerate the development and adoption of quantum technologies in that area or sector (QED-C, 2022b). Such a process is similar in both design and objectives to the development of sector-specific roadmaps for quantum technology adoption (Section 6.1.4).

6.1.3 Sector-specific and Government Advisory Boards

Another public-private collaborative approach to encouraging the adoption of quantum technologies could be based on a council or roundtable that facilitates co-operation and discussions among developers and users, as well as governments, academia, and other experts and stakeholders. Of the different possible approaches, this section examines two: (i) government advisory boards representing stakeholders from across a quantum ecosystem, and (ii) sector-specific boards representing adopters of quantum technology. The former is a commonly used model; instances have been established in both Canada and the United States, and tends to focus more on quantum technology development. By contrast, the latter model is less common and focused more on adoption.

National advisory councils can play an important role in advising government's on adoption

A commonly used model for public-private collaboration on new and disruptive technologies is a government advisory board. A quantum technology advisory board would ideally be composed of representatives and stakeholders from across a country's quantum sector and tasked with providing advice to governments on the development and implementation of a national quantum strategy. In the view of the panel, it is important to include a diverse range of quantum expertise beyond researchers and developers, such as potential users and adopting sectors. For example, advisory board expertise in IP will be key for Canada, in order to ensure that innovations in the quantum sector are not lost to other countries, and that Canadian companies protect and maintain their Freedom to Operate.

The Government of Canada has established such an advisory body, as announced in the NQS. This Quantum Advisory Council will provide independent advice to government regarding the implementation of the strategy and growing the quantum sector in Canada. The full council membership was announced in July 2023 and includes representatives from industry and academia, as well as from a business incubator (ISED, 2023b).

The Quantum Advisory Council resembles the National Quantum Initiative Advisory Committee (NQIAC) in the United States, which was established in 2019 by Presidential Executive Order (The White House, 2019), as required by the *National Quantum Initiative Act* (U.S. Congress, 2018). In May 2022, the NQIAC was elevated, again by Presidential Executive Order (The White House, 2022a), to the level of a Presidential Advisory Committee, thereby "highlighting that the National Quantum Initiative is a whole-of-government effort that rises above any one Federal agency" (NQIAC, n.d.).[15] The purpose of the NQIAC is:

> *to provide advice and guidance on a continuing basis to the President, the Secretary of Energy, and the National Science and Technology Council Subcommittee on Quantum Information Science (QIS), the National Quantum Initiative (NQI) program, and on trends and developments in quantum information science and technology.*
>
> Butler (2022)

Membership on the committee is composed of individuals "representing industry, universities, Federal laboratories, or other Federal Government agencies," and includes the Director of the Office of Science and Technology Policy, who serves as co-chair of the committee (Beitler, 2020).

Government-funded, sector-specific boards could accelerate adoption in various sectors

As noted in Section 6.1.2, among the most effective methods for identifying potential near-term applications of quantum technologies and facilitating their adoption are collaborative discovery processes specific to a particular sector or area. One model for such a process could be based on Ontario's sectoral councils of the 1990s. Ontario's sector-focused industrial strategy in that decade was linked to the Sector Partnership Fund (Gov. of ON, 1992), an initiative "to provide financial assistance to cooperative projects based on an approved strategy fashioned by key players in the sector" (Wolfe, 2002). To qualify for funding, a

15 Whereas, in its original iteration, NQIAC provided advice only to the Secretary of Energy and the Subcommittee on Quantum Information Science (SCQIS) of the National Science and Technology Council (NSTC) (The White House, 2019), it now also provides advice directly to the President and the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX) (The White House, 2022a).

sector had to develop a strategy, specific to itself, through a collaboration process that involved a wide range of key stakeholders and address that sector's internal and external challenges and opportunities, future prospects, and common goals and objectives, and draft a strategic plan to achieve them. Funding was made available for specific sector-wide initiatives described in the plan, including developing technological capabilities and specialized technological infrastructure. Responsibility for developing these strategies was largely devolved to the sectors themselves, which had to develop forums or councils to undertake this process, breaking with the historically top-down, hierarchical approach to industrial policy in the province (Bradford, 1998; Wolfe, 2002). While outcomes varied among sectors, the process itself was widely considered to be successful. It identified sector-specific strengths and weaknesses, and corresponding opportunities and challenges. It also facilitated the establishment of new relationships and the strengthening of existing ones among stakeholders within the sector, as well as the identification of shared interests and goals, and strategies to pursue them collaboratively (Wolfe, 2002).

A similar approach could be used to accelerate the uptake of quantum technologies in various sectors: governments could provide funding for sectors to collaboratively develop strategies for adopting quantum technologies into their operations, and fund specific sector-wide initiatives to implement those strategies. It could be implemented by requiring the development of a quantum technology roadmap for each sector that includes funding proposals for specific initiatives.

6.1.4 Technology Roadmaps

As quantum technologies advance from theoretical science to commercial products, the use of roadmaps can help accelerate their deployment and adoption. Roadmaps are widely used tools to facilitate the development and diffusion of new technologies, often focusing on specific technologies, sectors or industries, countries or jurisdictions. Roadmaps can help identify (i) specific objectives and priorities for quantum technologies in a particular firm, industry, or country, (ii) the practical steps required to achieve those objectives, and (iii) the roles and responsibilities of different actors in implementing those steps.

In addition, the roadmapping process can help to highlight and develop solutions to challenges impeding adoption, including institutional challenges related to innovation policy and lack of a quantum-ready workforce; legal and regulatory challenges related to IP, competition, standards, and trade; and social and ethical challenges related to security, privacy, and access to technology. The process can also help mitigate hype around quantum technologies by dispelling exaggerated claims about their capabilities, usefulness, or transformative potential for certain applications or sectors.

Roadmaps for specific quantum technologies have been published by developers, government agencies, and academic researchers

Nearly all major developers of quantum computers have released roadmaps that identify specific milestones they expect to achieve within the next several years (Langione *et al.*, 2019b). Furthermore, several governments have released roadmaps pertaining to specific quantum technologies or specific related issues. For example:

- the United Kingdom has developed a technical roadmap for quantum computing (Fruchtman & Choi, 2016);
- the U.S. Department of Energy has developed roadmaps for quantum interconnects[16] (ANL, 2022) and a quantum internet (van Dam, 2020);
- the U.S. Department of Homeland Security has partnered with NIST to develop a roadmap to help organizations prepare for and implement quantum-safe cybersecurity (U.S. DHS, 2022); and
- the European Committee for Standardization (an association of the national standardization bodies of 34 European countries) has developed a standardization roadmap for quantum technologies (CEN-CENELEC, 2023, n.d.).

Additionally, a wide range of roadmaps for specific quantum technologies have been developed in recent years by researchers and published in academic journals. Typically, these describe the current state of the technology, challenges for its future development, potential solutions to those challenges, and estimated timelines to technological maturity.

Sector-specific roadmaps for quantum technologies may help accelerate adoption

The development of a roadmap for the adoption of quantum technologies in a specific sector allows stakeholders to engage in a collaborative process of identifying the most relevant opportunities and challenges for quantum technologies in their area, understanding the potential benefits and risks, sharing information and best practices, developing intra-sectoral networks and value chains, and ultimately creating a common vision of the goals and objectives for quantum technologies in that sector. Several sectors expected to be early or high-value adopters of quantum technologies have developed their own roadmaps for quantum technology adoption:

16 These are technologies that "link and distribute coherent quantum information between systems and across different length scales to enable quantum sensing, communications, and computing" (ANL, 2022).

- In the defence sector, quantum technology roadmaps have been developed by Canada's DND (DND & CAF, 2021, 2023) and the Australian Army (Commonwealth of Australia, 2021).
- Scientific research organizations have developed roadmaps for the adoption of quantum technologies, including the European Organization for Nuclear Research (CERN) (Bilton *et al.*, 2021). In addition, a roadmap for the space-based deployment of cold atom quantum sensors was developed by representatives of Europe's astrophysics, cosmology, fundamental physics, geodesy, and Earth observation communities to inform the European Space Agency's science program (Alonso *et al.*, 2022).
- In Canada, the NRC has consulted with mining industry and quantum industry stakeholders, who noted the need to develop a roadmap to help drive the adoption of quantum technologies in the mining sector (NRC, 2017a).

Roadmaps can help countries or jurisdictions improve adoption

The development of national quantum technology roadmaps in specific countries or jurisdictions can help governments identify and prioritize particular sectors or industries for the adoption of quantum technologies. Indeed, adoption in Canada is likely to be substantially easier for quantum technologies that are aligned with the country's unique needs, which can be identified through the roadmapping process (as well as through sector-specific and government advisory bodies; see Section 6.1.3). For example, given Canada's large geographical size and lack of infrastructure in remote areas, satellite-based quantum communications may be particularly valuable. Other important features might include Canada's population size and demographics, the size and composition of quantum and non-quantum firms (i.e., large enterprises versus SMEs), Canada's innovation challenges, and the need to protect domestic IP.

National quantum technology roadmaps also typically provide advice and guidance, identify best practices, and list existing and planned initiatives, which may receive financial support from one or more orders of government. The roadmapping process provides a valuable opportunity to involve a wide variety of stakeholders in the development of national quantum strategies. Leading examples of roadmaps tend to involve all orders of government and identify opportunities for cross-sectoral collaboration among stakeholders from both the private sector and academia. The roadmapping process also creates opportunities for these stakeholders to collaborate on strategies and policies, as well as to share knowledge, information, and best practices.

Several foreign jurisdictions have developed national roadmaps for quantum technologies, including Australia (CSIRO, 2020), the European Union (E.U., 2016), Germany (Filipp & Leibinger, 2021), the Netherlands (QDNL, 2019), and the United Kingdom (UKNQTP, 2015). These roadmaps were often developed through consultation processes involving stakeholders from across the quantum ecosystem, including developers and users, academic and other research organizations, government agencies and regulatory bodies. For example, the roadmapping process in the United Kingdom was based on two workshops that brought together representatives from the academic, industrial, and regulatory sectors to prioritize national goals and commercialization opportunities, identify trends and drivers of quantum technology adoption, identify areas for collaboration and coordination, identify policy and regulatory challenges and enablers, and incorporate stakeholder perspectives on these issues (IfM *et al.*, 2014; UKNQTP, 2015).

In addition, quantum industry associations in some jurisdictions have developed their own roadmaps. For example, the European Quantum Industry Consortium (QuIC), an industry association for Europe's quantum sector, is developing a strategic roadmap to help inform government policy and support for Europe's quantum sector, as well as improve the quantum value chain in Europe (QuIC, n.d.-b).

In the NQS, the federal government has signalled its intention to launch a roadmapping exercise in collaboration with academic and industry experts that will "include detailed objectives, milestones and actions required of government, academia and industry to realize mission goals" (ISED, 2023d). The process will be carried out by three working groups each focused on one of the strategy's three technologies: (i) quantum computing, (ii) quantum encryption and communications, and (iii) quantum sensing. In the panel's view, this proposed roadmapping process is among the most promising aspects of the NQS with respect to the issue of quantum technology *adoption*, as it provides the most significant opportunities for potential users to address challenges and opportunities related to that adoption.

Roadmaps may help identify and mitigate gaps and barriers in supply chains for quantum technologies

As noted in Section 3.2, quantum technologies depend on complex supply chains that include key raw materials, manufactured components and equipment, and specialized manufacturing and fabrication facilities, many of which may be available only from a small handful of companies or jurisdictions. A detailed understanding of these supply chains can be useful in identifying challenges, opportunities, and bottlenecks on the path to commercialization, as well as help facilitate collaboration in the quantum sector. In the United States, NIST has tasked SRI International — a non-profit research institute that manages QED-C — with developing a quantum technology manufacturing roadmap (O'Shea, 2022; SRII, 2022). Undertaking a similar exercise could help Canada better position itself in the larger global quantum technology supply chains (as both an importer and exporter of materials and components) and develop cross-border partnerships that can help ensure these supply chains are stable and secure.

6.2 Competition, Regulation, and Standards

In Canada, both federal and provincial/territorial governments regulate economic activity. The Government of Canada may adopt laws, regulations, and policies governing many financial institutions (e.g., banks, insurance companies) and telecommunications providers (e.g., internet service providers, cable systems) (CRTC, 2018; OSFI, 2022b). Regulatory intervention (e.g., information security standards, data privacy rules) may incentivize the adoption of quantum technologies by relevant economic sectors even in the absence of technology-specific rules. In the panel's view, however, regulation is not a substitute for competition in driving adoption, but rather a complementary approach. For instance, pro-competition policy reforms could have a spillover effect on the adoption of quantum technologies in sectors characterized by a high level of vertical integration, such as Canada's telecommunications sector.

6.2.1 Competition

Pro-competition regulatory oversight can stimulate adoption by the telecommunications sector

Canadian quantum companies may face barriers in diffusing their technologies because one of their main potential end-users, the telecommunications sector, is not sufficiently motivated to leverage innovations to achieve competitive advantage (OECD, 2021a) (Chapter 4). The OECD 2021 survey of Canada highlights the need to enhance competition in the telecommunications sector as a policy priority (OECD, 2021a). In markets that are not sufficiently competitive or intrinsically susceptible to concentration, regulation can help achieve the objectives of a competitive marketplace (BTLRP, 2020). Although the *Telecommunications Act* lists increasing competitiveness as a policy objective, it lacks clear "policy guidance regarding reliance on competition" and underestimates the significance of market forces in the communications sector and their role in guiding and constraining the regulatory powers of the administrative state. Moreover, the Canadian Radio-television and Telecommunications Commission (CRTC) is not explicitly required "to monitor and assess ... the state of competition in key electronic communications markets" (BTLRP, 2020). In light of the identified legislative issues, the Broadcasting and Telecommunications Legislative Review Panel (BTLRP), created by the Government of Canada, recommended amending the policy objectives of the *Telecommunications Act*. The reform of the CRTC's discretionary authority to forbear from regulating service providers could emphasize the importance of competition as the guiding principle of regulation. Combined with the monitoring obligations mentioned above, these reforms could allow the CRTC to stay abreast of the state of competition and apply appropriate tools if intervention is required (BTLRP, 2020).

6.2.2 Regulation

The financial sector tends to adopt a risk-averse approach to technological innovations. This may slow down the adoption of several quantum technologies, including quantum-resistant cryptography (QRC) and, possibly, quantum key distribution (QKD). Regulatory involvement that imposes on the financial sector an affirmative duty to adhere to certain security and privacy standards could incentivize the adoption of quantum technologies that ensure regulatory compliance.

The Office of the Superintendent of Financial Institutions (OSFI) can rely on non-binding and technology-neutral instruments to encourage adoption

Canada's federal regulator, OSFI, is mandated under the *Office of the Superintendent of Financial Institutions Act* "to supervise financial institutions in order to determine whether they are in sound financial condition and are complying with their governing statute law and supervisory requirements" (GC, 1985c). OSFI can use various tools to carry out its mandate, such as "directions of compliance, disqualification, or removal of directors or senior officers" (Anand & Green, 2012). In addition, it is empowered to impose penalties under the OSFI Act (GC, 1985c).

Despite a variety of instruments at its disposal, OSFI prefers non-binding guidelines to regulations in key areas of its statutory mandate, including that of ensuring the technological readiness and cybersecurity of Canada's federally regulated financial institutions (Anand & Green, 2012). OSFI's guidelines document, *Technology and Cyber Risk Management,* issued in 2022, provides, among other things, that federally regulated financial institutions should "continuously monitor the currency of software and hardware assets used in the technology environment in support of business processes" and "proactively implement plans to mitigate and manage risks stemming from unpatched, outdated or unsupported assets and replace or upgrade assets before maintenance ceases" (OSFI, 2022c).

Although OSFI's guidelines are technology-neutral, the existing regulatory framework does not preclude it from encouraging financial institutions to adopt any quantum technologies that could help ensure compliance with technology risk management guidelines. Indeed, in its *Proposed Short-and-Medium Term Roadmap for an Evolving Digital Landscape*, OSFI notes its plan to clarify or consult on risk management and governance issues for quantum technologies (OSFI, 2022d). At the same time, it intends to avoid "developing a new regulatory system for new technologies" and will continue using flexible guidelines as the main instrument of supervision, "given the unique risks and vulnerabilities that vary with a [federally regulated financial institution's] size, scope, and complexity and risk profile" (OSFI, 2022a).

The CRTC does not set security standards, limiting its ability to mandate the implementation of quantum-safe communications networks

Under the *Telecommunications Act*, the CRTC ensures that telecommunications service providers (including internet and wireless service providers) render "reliable ... services of high quality accessible to Canadians in both urban and rural areas" (GC, 1993). Although the CRTC ensures that all providers act in the public interest, the *Telecommunications Act* does not mention security as a policy objective, and the CRTC is not responsible for "establishing baseline network security standards" for providers (BTLRP, 2020) (Box 6.5). This can potentially affect the CRTC's ability to mandate the implementation of quantum-safe communications networks.

Box 6.5 Security Best Practice Policy for Canadian Telecommunications Service Providers

In the absence of mandated rules and standards, the Canadian Security Telecommunications Advisory Committee (CSTAC) created the *Security Best Practice Policy* for Canadian telecommunications service providers (TSPs) (CSTAC, 2020). CSTAC was established in 2010 and its members include senior-level government officials from CSIS, ISED, Public Safety Canada, the RCMP, the Canadian Centre for Cyber Security, and representatives of the telecommunications industry, including Bell, Cogeco, Rogers, Shaw, and TELUS (ISED, 2020). The policy draws on various domestic and international sources (e.g., Communications Security Establishment, International Organization for Standardization, NIST) that deal with specific subject matter (CSTAC, 2020). These practices, however, are not legally binding, and there is no uniform regime applicable to network security within the interconnected Canadian telecommunications environment (BTLRP, 2020). CSTAC best practices are technology-neutral and are "intended to be high-level guidance that can be used to shape the implementation of specific controls at each [TSP]" (CSTAC, 2020).

In 2020, the BTLRP recommended amending the policy objectives of the *Telecommunications Act* "to include the promotion of the security and reliability of telecommunications networks and electronic communications services" (BTLRP, 2020). This could enable the CRTC to "register, collect information, and establish [security] standards for telecommunications market participants" (BTLRP, 2020). Moreover, the codification of mandatory security practices could allow the CRTC to mandate more extensive co-operation between TSPs and the Canadian Centre for Cyber Security, which is working on standards for the next generation of QRC (BTLRP, 2020; Cyber Centre, 2021).

Bill C-26 could drive the adoption of QRC by federally regulated sectors, but it confers broad discretionary powers to the federal government

In 2022, the Government of Canada introduced Bill C-26 (*An Act respecting cyber security, amending the Telecommunications Act and making consequential amendments to other Acts*) (House of Commons of Canada, 2022b). The bill proposes a legal framework for safeguarding the cybersecurity of Canada's key infrastructure, including the federally regulated financial, energy, transportation, and telecommunications sectors. Bill C-26 is the key element of the federal government's National Cyber Security Strategy, which, among other things, focuses on developing QRC algorithms and ensuring that vital systems are quantum-resistant (PS, 2022). If passed, the bill can give the federal government additional powers to order regulated industries to implement QRC. As of September 2023, the bill has been referred to the House of Commons Standing Committee on Public Safety and National Security (Parliament of Canada, n.d.).

Amendments to the *Telecommunications Act* proposed by Bill C-26 add the promotion of security as a new objective of telecommunications policy (House of Commons of Canada, 2022b). To advance this objective, the amendments empower the Governor in Council and Minister of Innovation, Science and Industry to order a TSP to take any necessary actions to secure the telecommunications system (Grant, 2022; House of Commons of Canada, 2022b). The minister, for example, could require TSPs to "enable optional security standards in telecommunications standards, establish effective multifactor authentication on internal- as well as customer-facing interfaces, or otherwise do anything that has been standardized somewhere" (Parsons, 2022). However, in the absence of a clear definition of a standard, it is difficult to determine whether the government is considering international or domestic standards, or whether it will require TSPs to adopt standards that will enable government access to their data traffic for the purposes of national security and law enforcement (Parsons, 2022).

Although Bill C-26 could eventually stimulate the adoption of QRC in federally regulated sectors, it has been criticized for secrecy and accountability deficiencies, and for failing to constrain the government's new supervisory powers (Parsons, 2022). Bill C-26 does not recognize that privacy or other Charter-protected rights may override the proposed security requirements (Parsons, 2022). Some commentators also criticize it for failing to address the ongoing issues with the CRTC's mandate, assigning instead additional regulatory responsibilities to ISED. This exacerbates the relatively unstructured role of the CRTC in the federal government and dilutes its accountability for potential regulatory shortcomings (Abramson & Bester, 2022). Moreover, ISED is not required to publish orders or regulations issued under the amended act and could prohibit the recipients from disclosing them. In some situations, the federal government could issue a regulation or an order that contradicts the CRTC's decision or overrides some aspects of it. Finally, regulatory compliance costs may threaten the viability of smaller providers (Parsons, 2022).

In addition to amending the *Telecommunications Act*, Bill C-26 proposes a new piece of legislation called the *Critical Cyber Systems Protection Act* (CCSPA) (House of Commons of Canada, 2022b). The CCSPA creates new duties for operators of essential systems and services (House of Commons of Canada, 2022b). These duties include establishing a regulated cybersecurity program, mitigating supply chain risks identified by the cybersecurity program, and complying with the cybersecurity directions of the Governor in Council. The CCSPA would also enable certain regulators (e.g., Bank of Canada; Canada Energy Regulator; Canadian Nuclear Safety Commission; OSFI; Minister of Innovation, Science and Industry; Minister of Transport) to issue orders and penalties for non-compliance. Human rights advocates and cybersecurity experts have criticized the CCSPA largely for the same reasons as the amendments to the *Telecommunications Act*; the CCSPA lacks compulsory mechanisms to constrain the abuse of new governmental decision-making and surveillance powers, including the ability to impose significant fines or imprisonment for non-compliance and to access sensitive personal data (CCLA, 2022).

6.2.3 International Trade and Standards

Connecting to international markets through trade agreements can help Canadian quantum companies expand their market size and boost the diffusion of quantum technologies. Although Canada's international trade agreements, such the *Canada-European Union Comprehensive Economic and Trade Agreement* (CETA) and the *Canada-United States-Mexico Agreement* (CUSMA), do not contain quantum-specific provisions, they establish a general framework with respect to trade in goods, services, and procurement that allows domestic quantum companies to access international markets (INDU, 2022a).

The Trade Commissioner Service (TCS) may not be well acquainted with industry-specific contexts

The TCS under Global Affairs Canada provides services and support to Canadian firms wishing to export their goods (TCS, 2023). When EKOS (2019) conducted quantitative and qualitative research among TCS clients to assess whether they were satisfied with its work, participants were asked what prompted them to contact the TCS. Most replied that they wanted to get basic information about doing business in a given market (61%) or assistance with international sales and marketing (48%). Other reasons included getting information about distribution channels (34%) and how to export goods to a market (32%) (EKOS, 2019).

While the majority of participants viewed the TCS as an important resource for dealing with international trade issues (particularly in the United States), client satisfaction varied substantially depending on the level of specialization (EKOS, 2019). Highly specialized firms were less likely to find TCS support useful, suggesting staff is not well informed about specific industry contexts. Since the nascent market for quantum technologies relies on a limited number of specialized buyers, the TCS may not be well equipped to support Canadian quantum companies wishing to export their technology. Some participants also suggested that the TCS "should provide more extensive assistance and should have greater expertise with the operations of governments in their markets, particularly on matters related to government contracting and procurement" (EKOS, 2019).

Standardization can boost international adoption of Canadian quantum technology

Standards developed pursuant to a transparent, accountable, and inclusive process can accelerate market uptake of quantum technologies, impacting a range of commercial applications. One of the main advantages of standards is that they reduce barriers to trade, making it easier for domestic companies to sell their technology internationally. Several international agreements, including CETA and CUSMA, aim to reduce technology's time to market by requiring or encouraging signatories to incorporate international standards in their technical regulations and recognize each other's conformity assessments (EA, 2017) (Box 6.6).

Box 6.6 Provisions on Standards in CETA and CUSMA

CETA contains a chapter on technical barriers to trade that encourages co-operation in technical regulations and standards to avoid unnecessary obstacles (EA, 2017). Article 4.2 of CETA requires that parties rely on international standards for their technical regulations and Article 4.4 provides for co-operation to ensure the compatibility of respective technical regulations (GC, 2017). CETA also includes a *Protocol on the Mutual Acceptance of the Results of Conformity Assessment* that establishes the mutual recognition of national accreditation and conformity assessment bodies. This means that a conformity assessment body in the E.U. tests domestic products for export to Canada according to Canadian rules, and vice versa. These provisions aim to facilitate trade and benefit smaller companies, for which paying testing fees in both jurisdictions can be prohibitive (EA, 2017).

CUSMA builds on the commitments of Canada, Mexico, and the United States under the World Trade Organization *Technical Barriers to Trade Agreement*. It promotes the use of international standards; provides national treatment for procedures aimed at recognizing conformity assessment entities (e.g., certification and inspection entities, laboratories); and allows representatives of states to take part in the development of standards, regulations, and conformity assessments by their foreign counterparts (GAC, 2018).

Participation in standards-setting can help ensure Canadian interests are advanced globally

Standards-setting can be used as an anticompetitive practice to favour some firms and exclude others (Section 5.4). Although an international standards-setting process should mitigate this issue, it is often dominated by well-coordinated domestic bodies that can promptly gather relevant information (Büthe & Mattli, 2014). The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), which account for about 85% of international product standards, are subject to such coordinated influence (Büthe & Mattli, 2014). The NQS acknowledges this problem and stipulates that "Canada must be represented at various tables to ensure that international standards reflect Canadian principles and global frameworks reflect the interests of Canadian industries" (ISED, 2023d).

The efforts of different departments and agencies, as well as interagency and interdepartmental co-operation, have supported Canada's leadership in international standards-setting processes for a variety of sectors, such as agriculture and food products, hazardous products, human and veterinary drugs, telecommunications, and natural resources (TC, 2021). The Digital Governance Standards Institute, an independent division of the Digital Governance Council, is accredited by the Standards Council of Canada to develop "digital technology governance standards fit for global use" (DGC, n.d.; DGSI, n.d.). Ensuring a similar, coordinated approach to standards-setting in the area of quantum technologies could address the imbalance of power in the international standardization process, help Canadian quantum producers and end-users better prepare for new or changing standards, and, ultimately, ensure that Canadian companies are able to diffuse their technology internationally. The coordination of standards-setting efforts is particularly important in light of Canada's 2022 *National Standards Strategy*, which identified quantum computing as a key global trend relevant to Canada's standards system (Standards Council of Canada, 2022).

6.3 Industry-led Approaches to Adoption

In addition to government-led interventions to drive the adoption of quantum technologies, there are also several approaches the quantum industry could explore to encourage adoption, including business-to-business partnerships and the provision of professional support services. Indeed, one of the most common and effective ways for businesses and other organizations to explore the adoption of quantum technologies is through some form of partnership with technology providers (IBM, 2018; Langione *et al.*, 2019b; Capgemini, 2022). This approach has been pursued by a wide range of industries looking to adopt quantum technologies.

> *Partnerships have already become the model of choice for most of the commercial activity in the field to date. Among the collaborations formed so far are JPMorgan Chase and IBM's joint development of solutions related to risk assessment and portfolio optimization, Volkswagen and Google's work to develop batteries for electric vehicles, and the Dubai Electricity and Water Authority's alliance with Microsoft to develop energy optimization solutions.*
>
> Langione *et al.* (2019b)

As noted in Section 2.1.1, there are significant advantages for potential users adopting a partnership or service-based approach to quantum technologies rather than developing in-house quantum capacity: (i) quantum technology is too complex and evolving too quickly for individual organizations to keep up; (ii) there is a shortage of, and tight competition for, highly qualified quantum specialists; and (iii) investing in the entire quantum stack infrastructure (i.e., hardware, software) is too costly and requires too much expertise (IBM, 2018; Capgemini, 2022). Thus, such arrangements represent a relatively low-cost, low-risk strategy for organizations seeking to understand the potential applications and benefits of quantum technologies, while at the same time providing benefits to developers in the form of industry-specific expertise and skills that can help them build use cases for particular sectors (Langione *et al.*, 2019b).

6.3.1 Professional Services

A popular private sector-based approach to encourage the adoption of quantum technologies focuses on attracting potential users by offering access to quantum computing as a service (QCaaS). This approach often goes beyond simply providing cloud-based access to quantum computers; rather, the key component is the provision of professional support services and training opportunities to companies that help them identify and co-develop quantum applications. This approach can help potential users understand the possible applications and benefits of quantum technology for their business, regardless of the lack of demonstrated quantum advantage for NISQ computers for practical applications.

Generally, these business models involve working directly with clients to identify practical use cases for quantum computing in a business or determine how quantum computing can be applied to problems faced by these clients. The providers then work to reformulate the problem to be implementable on specific quantum computing hardware/software. The providers implement the application, which usually involves some degree of testing and piloting. Finally, the end product is often supported or maintained by the provider. Providers may also offer some level of training or education for their clients to help develop their in-house quantum computing capabilities. Current examples of companies in Canada pursuing this type of professional service-based approach include D-Wave, IBM, 1QBit, and Xanadu, among others. See Figure 6.1 for an illustration of the process by which a business may come to use cloud-based quantum computing.

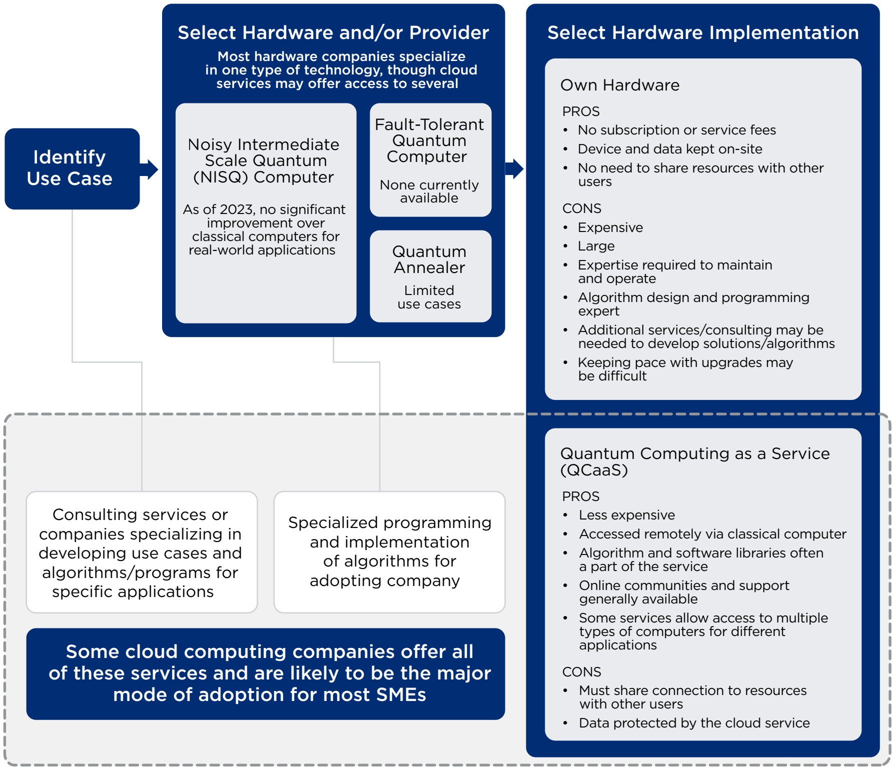


Figure 6.1 How a Business Could Partner with a Quantum Computing Provider

6.3.2 Regional Quantum Hubs

Another industry-based approach to accelerating the adoption of quantum technology is through *quantum hubs* — regional centres for quantum R&D and innovation in which quantum technology companies establish partnerships with universities, other companies, government agencies, and other organizations to provide access to their technology as well as expertise, consulting, and training programs. This can help partner organizations identify use cases and commercial applications for quantum technologies, facilitating wider adoption. Such hubs have been established in several countries, including the Netherlands and Canada.

For example, as noted in Section 3.1.3, an IBM Quantum Hub was established in Canada at Institut quantique at Université de Sherbrooke in 2020. The hub includes several partners — such as CMC Microsystems (CMC Microsystems, 2020) and

Lockheed Martin (Mallah, 2021b) — and is undertaking collaborative projects with the Bank of Canada, Statistics Canada, and Thales (Mallah, 2021a). With the announcement of the Quebec-IBM Discovery Accelerator and the installation of an IBM quantum computer in Bromont, Quebec, the IBM Quantum Hub governance model was moved to Plateforme d'Innovation Numérique et Quantique ($PINQ^2$), a non-profit organization founded by the Ministère de l'Économie, de l'Innovation et de l'Énergie du Québec (MEIE) and Université de Sherbrooke in 2020.

Government investments in similar regional hubs for quantum innovation may represent an opportunity to encourage future adoption. Indeed, in some cases, IBM quantum hubs are partially subsidized by governments. For example, the Government of Quebec has invested $131 million in the development of the IBM Quantum Hub at Université de Sherbrooke (Gov. of QC, 2022). Such investments are intended to encourage partnerships (both domestic and international), attract researchers, and train students.

Regional hubs are based on an open innovation paradigm

Regional quantum hubs — and IBM's approach in particular — have been described as an attempt "to build the [quantum computing] community through collaborative R&D and user open innovation" (MacQuarrie *et al.*, 2020). *Open innovation* refers to "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and to expand the markets for external use of innovation, respectively" (Chesbrough *et al.*, 2006). It involves both *inbound* knowledge flows (i.e., opening a company's internal innovation process to external knowledge inputs in order to drive innovation) and *outbound* knowledge flows (i.e., allowing proprietary knowledge to flow outside of a company in order to drive market adoption of its innovations) (Chesbrough, 2017). This outbound flow of knowledge allows firms to create value by enabling others to use the technology they develop (Wang *et al.*, 2012). Furthermore, *local* open innovation among firms in close geographical proximity can help strengthen regional innovation systems (Leckel *et al.*, 2020).

Since the concept of open innovation was introduced in 2003, subsequent studies over the past two decades have indicated that its use "has a positive influence on firm performance" and can produce beneficial collaborations that "foster the exchange of knowledge and reduce technological inefficiencies" (Bigliardi *et al.*, 2020). Moreover, the U.S. National Academy of Sciences has argued that such an approach (i.e., an "open ecosystem that enables cross-pollination of ideas and groups") is needed to accelerate quantum technology development and adoption (NASEM, 2019).

6.3.3 Industry Consortia

Many countries and jurisdictions currently leading in the quantum space have established industry associations or consortia to advance the development and adoption of quantum technologies. These include Quantum Industry Canada (QIC, 2020), the U.S. Quantum Economic Development Consortium (QED-C, 2020a), the European Quantum Industry Consortium (QuIC, n.d.-a), and Japan's Quantum Strategic Industry Alliance for Revolution (Q-STAR, n.d.-a). In January 2023, these four organizations signed an MOU that established the International Council of Quantum Industry Associations, which aims to "strengthen communication and collaboration among the participating consortia on goals and approaches to the development of quantum technologies" (QED-C, 2023b).

Quantum industry consortia undertake a variety of activities, including:

- facilitating collaboration and coordination, and developing strategic partnerships with stakeholders from across a country's quantum ecosystem, including governments, universities, research organizations, and investors;
- identifying use cases and applications in collaboration with potential users;
- informing the development of standards and benchmarks;
- supporting education, training, and workforce development;
- engaging in public outreach and communications;
- assisting in the development of domestic and international supply chains (including enabling technologies);
- helping companies protect and share their IP;
- promoting ethics and public trust in the use of quantum technologies; and
- undertaking research about quantum technology commercialization, adoption, and economic impact (QED-C, 2020b, 2020c; QIC, 2020; Q-STAR, n.d.-b; QuIC, n.d.-c).

6.4 Building a Quantum-ready Workforce

Quantum technologies require a high level of expertise to build, install, operate, and maintain. Highly qualified personnel (HQP) with a variety of expertise will be needed across the value-chain, but organizations in and around the quantum technology sector are facing a significant shortage of HQP specialized in quantum science and technologies (Metz, 2018; Kaur & Venegas-Gomez, 2022; NSTC-SCQIS, 2022). Not only will the demand for quantum skills continue to increase as these technologies develop and new applications and use cases are identified (Kaur &

Venegas-Gomez, 2022), but there is also intense global competition to attract and retain quantum talent (Mahboubi, 2022).

To create the enabling conditions for quantum adoption, Canada will need to develop a quantum-ready workforce by pursuing strategies to train, attract, and retain quantum HQP. This can be done in two complementary ways: training and education, and immigration. Moreover, developing a quantum-ready workforce will require coordination among a wide variety of actors, including governments, academic institutions, industry, professional societies, non-profit organizations, and international partners (NSTC-SCQIS, 2022). The state of quantum education and training offered in some foreign jurisdictions is described below.

6.4.1 Training and Education

Canada will need more HQP to keep up with quantum technologies, but lacks data on future needs

A variety of sources suggest there is a shortage of HQP with quantum-related skills (USGAO, 2021; WEF, 2022a; ISED, 2023d). There are several levers that can address this shortage related to the number of people seeking training in quantum fields and the types of training they can access. As of 2023, quantum-related training in Canada is almost exclusively offered at the graduate level, though programs offered at the undergraduate and college levels will be needed to keep up with future demand for technical expertise (USGAO, 2021; Kaur & Venegas-Gomez, 2022; WEF, 2022a). Notable, however, is a lack of data attempting to predict the magnitude of the HQP deficit in Canada.

Box 6.7 The Cybersecurity Industry: A Pressing Need for Specialized Quantum Training

Cybersecurity is a rapidly growing industry that will need to implement new forms of QRC and security protocols once quantum computers are fully realized and more widely adopted. A 2021 survey found that, even in advance of this adoption, the number of cybersecurity professionals in Canada grew from 84,000 in 2019 to 123,696 in 2021. Despite this growth, it is estimated that Canada continues to have a workforce gap as large as 25,000. Because of this rising demand, many governments are working to develop quantum-safe security strategies, including increased funding for research, development, infrastructure, standardization protocols, and training.

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Cybersecurity professionals in Canada possess all levels of education, with the plurality (38%) having bachelor's degrees. Master's graduates are the second-most represented (28%), followed by high school graduates (12%), holders of two-year college degrees (11%), and PhDs (10%). Currently, a variety of post-secondary institutions offer cybersecurity training, but there are relatively few quantum-specific training opportunities.

(GACG, 2021b)

Expanding Canada's quantum workforce depends on recruiting from underrepresented groups

As noted in Chapter 4, STEM disciplines remain heavily dominated by men in Canada. Indeed, the disciplines with the greatest involvement in the quantum industry are among those with the lowest representation of women, such as computer science, engineering, mathematics, and physical sciences (Aiello *et al.*, 2021). In addition, there is a need to increase the racial and ethnic diversity in the quantum field (Aiello *et al.*, 2021; Lee & Serles, 2021). As such, experts have recommended expanding STEM recruitment strategies in elementary and secondary school, with an additional focus on recruiting more women and girls (NRC, 2017b). Likewise, quantum courses at the post-secondary level could be designed to better highlight the contributions of underrepresented groups to the field (Kaur & Venegas-Gomez, 2022).

Education reform will be needed to develop a quantum workforce

In 2017, the NRC consulted quantum industry stakeholders about educational reforms to encourage the development of a quantum workforce. Suggestions included:

- additional STEM recruitment strategies in elementary and secondary school;
- creating joint physics-engineering degree programs in quantum science and technology;
- training students in quantum technologies entrepreneurship;
- creating educational programs that specifically focus on transferring expertise from quantum information science to quantum technology development; and
- creating mechanisms to provide students with greater access to quantum research facilities and programs in different parts of Canada, including national laboratories (NRC, 2017b).

Developing a quantum workforce requires industry-academic coordination and collaboration

Building a quantum-ready workforce will likely require a combination of traditional academic education and hands-on industry training in real-world projects (Dunlop, 2019; Kaur & Venegas-Gomez, 2022). There is a consensus among stakeholders in the quantum industry that graduates become more valuable candidates in the employment market when they acquire industry training through internships or other programs (Kaur & Venegas-Gomez, 2022). Practical, hands-on training can help students strengthen and refine their understanding of complex abstract concepts in quantum theory, develop the skills and experience desired by prospective employers, and provide them with insight about the types of work they can expect in a quantum career (Aiello *et al.*, 2021). Furthermore, the need for industry-based training is due in part to the rapid pace of innovation in quantum technologies, which presents challenges when it comes to developing standardized and up-to-date classroom and lab-based curricula (Aiello *et al.*, 2021). As such, careers in quantum technology are likely to require continuous learning, potentially more so than careers in other STEM fields.

To address this issue, universities will need to develop more industry- and job-focused academic courses in quantum science and technology, as well as more partnerships with industry to build clearer quantum career paths (NRC, 2017b; Aiello *et al.*, 2021; Kaur & Venegas-Gomez, 2022). It may be helpful if the quantum industry could better articulate long-term personnel requirements, in order to help universities and governments establish priorities for training and strategic investments (NRC, 2017b). For example, information about skill demands in the quantum sector could help inform the creation of industry-focused master's programs (Kaur & Venegas-Gomez, 2022).

Programs in Canada that facilitate academic-industry collaboration in quantum include Mitacs and the NSERC CREATE Quantum Computing Program. Dunlop (2019) recommends that a quantum strategy for Canada build on the success of these programs by providing dedicated funding to allow Mitacs to develop a targeted quantum program, as well as doubling the size of NSERC's CREATE quantum stream and modifying it to allow for renewal of funding for successful projects. The NQS identified Mitacs as an important part of its Talent pillar, committing $40 million to support programming (ISED, 2023d). In addition, several institutions in Canada are pursuing academic-industry partnerships to enhance the quantum education and training of graduates, including the Quantum Algorithms Institute in British Columbia, Quantum Alberta, the Institute for Quantum Computing at the University of Waterloo, and Institut quantique at Université de Sherbrooke. Early successes from these collaborative initiatives could be studied to inform the development of similar programs across Canada. Likewise, the University of Calgary's professional master's program is designed from the ground up by industry experts so that it can provide students with the practical skills industry needs.

A quantum-ready workforce will require qualifications other than a PhD

A variety of paths can lead to a career that intersects with quantum technologies (Kaur & Venegas-Gomez, 2022). While it is rare for a graduate with a bachelor's degree to enter directly into a quantum technology role, there are increasingly more opportunities to specialize after graduation. Engineering physics degrees (such as those offered by Polytechnique Montréal) have broad offerings that allow students to focus on quantum technology (Universities Canada, 2022). Courses in computational chemistry at the University of Manitoba are additional examples of application-based quantum training. The Quantum Information program at Université de Sherbrooke blends quantum-specific training with communications technologies. The panel also notes that, because of the anticipated widespread adoption of quantum technologies, training at a variety of levels — on the development and adoption side, as well as less technical training for management and policy-makers — will need to be further developed and more widely available.

A 2019 survey of the quantum industry found that graduates with PhDs were the most sought-after job candidates (Fox *et al.*, 2020). However, while some roles require highly advanced quantum knowledge and skills that can only be acquired through a doctoral degree, there are many other experts — including engineers, software developers, and technicians — who contribute to the design, marketing, sales, and support of quantum technologies. These roles often require less formal education than a PhD and deserve consideration when curricula and training programs are being designed for a quantum workforce (Aiello *et al.*, 2021). In the panel's view, as adoption continues to increase and companies make greater use of quantum technologies, these roles will become ever more important. To address this issue, universities could create multidisciplinary courses in quantum technologies for degree programs in computer science, engineering, business, and finance, and encourage graduates from these sectors to explore careers in the quantum industry (Kaur & Venegas-Gomez, 2022). Non-academic quantum career pathways can help fill gaps in education and training.

Beyond academia, there are a variety of options to help encourage upskilling and re-skilling for the quantum technology sector, and to fill gaps in education and training. These include online courses, industrial educational programs, community networks, and even game-based learning (Kaur & Venegas-Gomez, 2022). Several major quantum computing companies provide educational and training materials designed for both students and non-students with previous computing experience. For example, IBM provides an open-source textbook for Qiskit, its open-source software development kit, including online courses (IBM, n.d.-b); Microsoft's Azure Quantum cloud computing service includes educational curricula and other resources for educators (Microsoft, 2022); and Google Quantum AI provides online tutorials and labs, as well as workshops for educators (Google, n.d.). D-Wave also offers a training program to enable adopters to use their Leap system (D-Wave, n.d.).

Foreign jurisdictions are preparing quantum-ready workforces

Other jurisdictions have begun drafting strategic plans to develop their quantum workforces. If Canada is to keep pace, it will need to do the same. For example, while many countries (including Australia, France, Germany, and the United Kingdom, as well as Canada) have released national quantum strategies that include talent development, few countries aside from the United States have QRC programs that include talent development (GACG, 2021b).

In the United States, the National Science and Technology Council released a national strategic plan for quantum workforce development in 2022. The strategy listed four key approaches to building a quantum workforce: (i) identifying and understanding the workforce needs of the quantum sector, over both the short and long terms; (ii) introducing broader audiences to quantum information science and technologies; (iii) addressing quantum-specific gaps in professional education and training; and (iv) making careers in quantum more accessible and equitable (NSTC-SCQIS, 2022).

The E.U. Quantum Flagship initiative includes the Quantum Technology Education Coordination and Support Action (QTEdu CSA) project, which is intended to "assist the European Quantum Flagship with the creation of the learning ecosystem necessary to inform and educate society about quantum technologies" (QTEdu, n.d.-b). It provides access to resources such as educational curricula, programs, courses, training, and evaluation tools, and it also runs pilot projects across Europe aimed at education, industry collaboration, outreach, and awareness (QTEdu, n.d.-c). Moreover, QTEdu CSA has developed a set of "qualification profiles" for those working in quantum technologies that describe specific skills and competencies acquired through training and education, and that prepare individuals for specific roles in the quantum sector. This is intended to "facilitate the planning and design of education and training projects" in quantum technologies (QTEdu, 2022).

In the United Kingdom, one of the objectives of the National Quantum Technologies Programme is to grow, attract, and retain talent through educational curricula, fellowship programs, and industry-engaged skills training (UKRI, 2020a, 2021).

6.4.2 Immigration

In addition to developing talent domestically, Canada may need to rely on immigration to build its quantum workforce. In both Canada and the United States, businesses and universities have expressed concern that, without reform to immigration policies and priorities, they will be unable to build and adopt quantum technologies (Metz, 2018; Simmons, 2022). In the panel's view, this concern is well founded; it is likely that Canada's immigration system for skilled workers and researchers may need to be reformed in order to successfully attract and retain the international HQP necessary to develop a quantum-ready workforce.

It has been suggested that, to build this workforce, "Canada needs the kind of fast-track immigration programs that fuelled the telecom boom in the 1990s" (Simmons, 2022). During that period, the ICT sector grew to become a significant part of the Canadian economy, increasing from 3.7% of real GDP in 1995 to 5.6% in 2000, with an annual growth rate of 4.3%, compared to 1.3% for all other industries (ICTC, 2012). However, such growth would not have been possible without immigration, which helped meet the demand for technical skills in the ICT labour market — in 2001, 32% of workers in that labour market were immigrants (ICTC, 2012); by 2016, it was 40% (Cameron & Faisal, 2016).

The Global Talent Stream under Canada's Temporary Foreign Worker (TFW) program could help attract HQP — it is designed to help businesses access highly skilled foreign talent with dedicated, faster application processing times (ESDC, 2022b). To be eligible for the Global Talent Stream, applicants must either be referred to the program by one of the stream's designated partners or apply for a position on the Global Talent Occupations List, which is based on National Occupational Classification (NOC) codes (ESDC, 2022a).

While the TFW program can help quickly attract the foreign HQP necessary for a quantum workforce, other immigration programs can help retain those workers in Canada. For example, there is evidence that immigration programs that involve two-step selection processes have been effective for both improving the success rate of immigrants as well as retaining talent in Canada (Hou *et al.*, 2020). Skilled workers admitted under the TFW program may later gain permanent residency through the Canadian Experience Class (CEC) program or the Provincial Nominee Program (PNP). Indeed, while many immigrants working in the ICT sector were admitted under the TFW program, as of 2016, only about 4% were temporary workers, while 96% were permanent residents or naturalized citizens (Cameron & Faisal, 2016).

Finally, Canada can also attract quantum HQP by appealing to foreign entrepreneurs who are developing start-ups. Canada's Start-Up Visa Program targets immigrant entrepreneurs who have the potential to build businesses and create jobs in Canada (GC, 2022b); it includes pathways for quantum start-ups through the Creative Destruction Lab's quantum stream (Dunlop, 2019).

Foreign students and researchers face immigration challenges

In addition to targeting skilled foreign researchers and workers in the quantum industry, Canada will also need to attract international students to develop a quantum-ready workforce. However, its ability to do so may be hindered by both high tuition fees and a high cost of living, as well as immigration challenges (NRC, 2017b; Ferreira & Klütsch, 2018; Grewal, 2022). This could be addressed by fast-tracking immigration processes for international students, and by providing dedicated scholarships and fellowships. In addition, collaboration with international networks may help facilitate the exchange of students across borders (NRC, 2017b).

Canada also faces challenges retaining international students. For example, the Express Entry system, launched in 2015, has created systemic barriers to foreign students seeking permanent residency in Canada and entry into the Canadian labour market (Grewal, 2022). It has been suggested that Canada could address these barriers by reforming the Express Entry system to account for both informal and student work experience, such as teaching and research assistantships that are currently ineligible under the program, as well as providing more opportunities for work experience to students (Grewal, 2022).

Similarly, high fees for visas and work permits for researchers may result in quantum talent moving to jurisdictions where such fees are affordable or waived. Short-term contracts (and changes in contracts) that require frequent visa renewals may also discourage researchers from remaining in Canada. Visa renewal can be an onerous process and take several months, during which a person may be forced to leave the country, thereby taking on additional financial burdens. In addition, some immigrants may face social or cultural challenges, as well as linguistic barriers (Malik *et al.*, 2022).

In short, governments can help Canadian organizations attract and retain foreign quantum researchers by reforming visa policies and practices, such as creating visa categories for quantum researchers (and their families) with waived or reduced fees, including shorter-term visas for conferences and internships; reducing the processing time of visas for quantum researchers; allowing researchers and their families to stay in the country while their visas are being renewed; allowing them to change jobs, such that their visas are not tied to a specific employer or organization; and allowing both researchers and their families to access social benefits (Malik *et al.*, 2022).

7

Framework for the Responsible Adoption of Quantum Technologies

Because quantum technologies present ethical, social, and legal challenges, in this chapter the Panel outlines a number of policy interventions that can prevent or mitigate those challenges and maximize the benefits of these technologies. A responsible approach to the adoption of quantum technologies relies on state-sanctioned and self-regulating measures, including quantum impact assessments, data protection and governance, controlled access to specific quantum technologies, soft law mechanisms, and responsible research and innovation. In the final section of this chapter, the panel reflects on its findings and the path forward for the adoption of quantum technologies in Canada.

7.1 A Responsible Approach to Innovation

From a governance standpoint, the adoption of quantum technologies by different economic sectors requires a responsible approach to innovation,[17] which anticipates multiple plausible outcomes of technological change, also known as the *anticipatory governance framework* (de Jong, 2022; Perrier, 2022). According to Guston (2008), anticipatory governance refers to a society's capacity "to manage emerging knowledge-based technologies while such management is still possible." The first pillar of the anticipatory governance framework consists of taking advantage of known policy responses to technologies with wide-ranging impacts on society (e.g., electricity, cars, AI, nanotechnology) (de Jong, 2022). This historic analysis demonstrates that governance instruments should be designed to consider key aspects of quantum technology adoption such as public perceptions and engagement, regulatory frameworks, and international co-operation (de Jong, 2022). The second pillar of the anticipatory governance framework considers the needs of different stakeholders (e.g., states, the private sector, civil society groups) because each may develop its own governance methodologies in response to the benefits and risks presented by quantum technologies (Perrier, 2022). As such, the anticipatory governance framework may impose constraints on the market-driven adoption strategies examined in Chapter 6.

7.1.1 Quantum Impact Assessments

Within the anticipatory governance framework, scholars have proposed quantum impact assessments (QIAs) to address and rectify the potential harms of quantum technologies (Kop, 2021c; Dekker & Martin-Bariteau, 2022). Several foundational rules for QIAs applicable across different quantum technologies include:

17 Some panel members note that, due to different conceptions of responsibility, *responsible adoption of quantum technologies* can be understood broadly as a process that takes various ethical and social issues into account.

1. *Taking care of the integrity of quantum systems, stored information and transfer thereof, and audit the information processing by quantum systems.*
2. *Ensuring traceability, testability and predictability of the quantum system's actions.*
3. *Respecting, not infringing, third party intellectual property rights.*
4. *Respecting people's privacy, confidentiality of information, the core ethical guidelines and the sector-specific laws and regulations of the quantum application.*
5. *Clarifying and delineating responsibilities in the development-components-application-service provider chain.*

Kop (2021c)

To develop a domestic QIA, policy-makers in Canada could draw on instruments that promote the responsible use of AI by the federal government, such as the Treasury Board of Canada *Directive on Automated Decision-Making* (ADM Directive), accompanied by an algorithmic impact assessment (AIA) tool (GC, 2023d) (Box 7.1). The ADM Directive aims to reduce the risks presented by AI to people in Canada by imposing conditions on the purchase and use of automated decision-making systems by certain departments. It requires that these departments conduct and publish AIAs, which they must repeat in case of changes in a system's functionality (GC, 2023d).

A similar approach to AI risk management (but supported by stricter enforcement measures) is considered in the E.U.'s proposed *Artificial Intelligence Act* (E.C., 2021). The draft framework classifies systems based on their potential for negative impacts on fundamental rights (e.g., human dignity, privacy, non-discrimination, freedoms of expression, information, and association), health and safety, and the rights of consumers and workers. The act establishes responsibilities and guardrails based on the level of risk, including banning the use of certain systems that are at odds with public values or that present significant risks to people.

Box 7.1 AIA Under the ADM Directive

In accordance with the ADM Directive, federal departments that plan to use automated decision-making systems need to evaluate whether a system's decisions would impact individual or collective rights, health and well-being, economic interests, and ecosystem sustainability. Following the assessment, the system is assigned one of four impact levels:

Level I: little, reversible, or no impact;

Level II: moderate, short-term, and reversible impact;

Level III: high, ongoing, and difficult-to-reverse impact; and

Level IV: very high, irreversible, and perpetual impact.

The level of impact determines applicable risk mitigation measures, from peer review and notifications about the use of the system to requiring special authorization and human supervision for systems classified as "high risk."

(GC, 2023d)

Domestic reforms in the area of AI governance will likely have implications for procedures governing QIA, particularly quantum machine learning. In this regard, the *Artificial Intelligence and Data Act* (part of Bill C-27) proposes an impact-based framework to regulate the use of AI systems in the private sector (House of Commons of Canada, 2022a). However, the act was criticized for failing to directly address some important aspects of AI governance (i.e., the definition of *high-impact systems*, which systems are subject to strict requirements, the penalties and the criteria for imposing them) and leaving them to regulations instead (Dekker & Martin-Bariteau, 2022). As of September 2023, the bill has not passed.

7.1.2 Data Protection and Governance

As noted in Chapter 4, some quantum technologies present significant risks to privacy. In some cases, existing data protection and governance rules may help mitigate these risks. However, new policies to govern public sector use of highly invasive technologies, including quantum sensors, are likely needed. In addition, data protection laws trail technological developments. Legislative proposals, such as Bill C-27, do not consider the potential risks arising from the use of quantum technologies, particularly in the context of data de-identification (Dekker & Martin-Bariteau, 2022). Although researchers have demonstrated that developments in data science and AI require complex anonymization to protect privacy, the Government of Canada's approach to re-identification risk management was unclear even before the advent of quantum technologies. Despite these technologies' ability to increase the vulnerability of sensitive information with a longer lifespan (e.g., health data, social insurance numbers), these risks are not addressed by the existing federal legal framework (Dekker & Martin-Bariteau, 2022). Due to Canada's federalism, ensuring privacy requires policy interventions by various orders of government.

7.1.3 Controlled Access to Quantum Technologies

Due to their potential to cause harm, quantum technologies are sometimes compared to nuclear technologies. This analogy is helpful when considering who should have access to quantum technologies and under what circumstances (Dekker & Martin-Bariteau, 2022). For example, the *Nuclear Safety and Control Act* contains mechanisms that limit the "risks to national security, the health and safety of persons and the environment" presented by "the production, possession and use of nuclear substances" (GC, 1997). The act created the Canadian Nuclear Safety Commission (CNSC), whose mandate is to regulate the production, use, and possession of nuclear substances; conduct inspections; and impose requirements on people and organizations participating in activities associated with nuclear substances. The CNSC also conducts education campaigns to inform the public about nuclear-related risks (GC, 1997; CNSC, 2023).

Similarly, the *Patent Act* contains additional security measures that might limit patent rights related to the production, application, or use of nuclear energy (i.e., the security exception) (WTO, 1947; WIPO, 2012). That legislation requires that the CNSC be notified prior to the examination or public disclosure of such patents (GC, 1985d), while the *Nuclear Energy Act* gives the Minister of Energy and Natural Resources a pre-emptive right to acquire these patent rights in the interest of national security (GC, 1985f).

Canada adopted the *Chemical Weapons Convention Implementation Act*, which has a similar legal framework for toxic chemical agents that may be used to create chemical weapons (GC, 1995). The *Human Pathogens and Toxins Act* requires an authorization to possess, handle, produce, store, transfer, import, export, release, and use pathogens and toxins; classifies pathogens based on level of virulence; and imposes strict security requirements (GC, 2009). These restrictions on nuclear substances, chemical materials, toxins, and pathogens are in addition to restrictions imposed under the *Export and Import Permits Act* (Chapter 5).

These legal frameworks could guide the regulation of quantum technologies in those cases where it is necessary to prevent malicious actors from accessing them. Promising risk mitigation practices include a vetting process for potential users, the licensing of technology, and record-retention policies. In addition, regulatory oversight — creating a specialized federal agency or delegating the mandate to an existing one — could facilitate controlled access and use (Dekker & Martin-Bariteau, 2022).

7.1.4 Soft Law Mechanisms

Because laws and regulations often face challenges, softer governance approaches may offer greater flexibility, though potentially at the expense of enforceability, accountability, and transparency. Johnson (2019), for example, suggests that advantages and disadvantages of soft law mechanisms implemented in the nanotechnologies sector can inform potential soft law governance strategies for quantum technologies. First, voluntary codes of conduct can be used to establish key principles and practices for quantum governance, which can become more comprehensive and context-specific over the long run. Second, third-party standards can help ensure common terminology and performance indicators for quantum technologies, and encourage socially responsible innovation; these, however, often lack transparency and accountability. Finally, voluntary regulatory programs can enhance information-gathering practices and public-private co-operation, but they also require incentives to stimulate industry buy-in and may become fragmented due to national security concerns. Although soft law instruments lack the force of law, they can be enforced through alternative measures (e.g., by insurance companies or through contractual obligations). Among the listed soft law mechanisms, third-party standards are sometimes adopted into national regulations and become legally binding (Johnson, 2019).

7.1.5 Responsible Research and Innovation

Social acceptance of technology is an important element of adoption strategies (de Jong, 2022). Public engagement is an important pillar of any responsible research and innovation (RRI) approach to the wider adoption of emerging technologies (this is sometimes known as *responsible innovation,* or RI)[18] (Ten Holter *et al.*, 2022). Von Schomberg (2012) offers the following definition of RRI:

> *A transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society).*

18 While RI identifies shared academic principles to improve the social implications of technology, RRI is focused on the implementation of these principles by policy-makers (Owen & Pansera, 2019).

RRI aims to incorporate ethical, legal, and social considerations into the R&D process, while directing innovation toward socially beneficial outcomes (KPMG Australia & Sydney Quantum Academy, 2021). It is an anticipatory approach to technology governance because it focuses on involving diverse actors at the outset of R&D, rather than solving problems post-implementation (KPMG Australia & Sydney Quantum Academy, 2021; de Jong, 2022). It does not assume that the public needs to be educated about emerging technologies; rather, it promotes dialogue among different stakeholders (Ten Holter *et al.*, 2022). Key elements of RRI include consultations and co-operation with stakeholders to anticipate the outcomes of adoption and responding to the results of consultations and reflections (Stilgoe *et al.*, 2013). Eventually, RRI may facilitate the adoption of a technology by society, improve the technology itself, and mitigate its negative effects (Ten Holter *et al.*, 2022). RRI has been applied to nanotechnology (Kjølberg & Strand, 2011), AI (Brundage, 2016), and synthetic biology (Macnaghten *et al.*, 2016). Several foreign research programs focusing on quantum technologies include RRI as a cross-cutting approach (Box 7.2).

Box 7.2 RRI Approaches to Quantum Technologies

Australia: The Responsible Innovation Future Science Platform and the Australian Research Council's Centre of Excellence for Engineered Quantum Systems funded a post-doctoral fellowship that examines the role of responsible innovation in technology design and use (KPMG Australia & Sydney Quantum Academy, 2021).

European Union: One approach to RRI developed in the European Union focuses on public engagement, open access, gender equality, ethics, science education, and governance (RRI Tools, n.d.). The Horizon 2020 Research and Innovation Programme funded QuantERA, a European network of public research-funding organizations, which in turn developed *Guidelines in RRI in QT* (QuantERA, n.d.).

The Netherlands: The Dutch Research Council introduced a research program that looks at the social impacts of quantum technologies, making nearly €2.9 million available to projects with four- to five-year-long projects (NWA, 2021).

(Continues)

(Continued)

United Kingdom: The Engineering and Physical Sciences Research Council implemented the AREA Framework (Anticipate, Reflect, Engage, Act) and encourages all researchers to follow it as a pathway to RRI (UKRI, 2022). In 2019, UK Research and Innovation funded a project that is designing “a methodology for combining participatory design and responsible research and innovation approaches in quantum technologies” (UKRI, n.d.).

Researchers in the United Kingdom have already conducted some RRI activities for quantum technologies. In 2017, 77 people of different socioeconomic and educational backgrounds participated in a public dialogue on quantum technologies (EPSRC, n.d.). Participants showed particular interest in quantum technologies that could save or prolong life (e.g., health technologies, humanitarian applications), improve efficiencies in healthcare, and advance national and individual security. However, they expressed concerns about the implications of quantum technologies for the digital divide, job losses in analytical and logistical roles, climate change, and the international arms race. Hacking, cyber warfare, and concealing criminal activities were all seen as potential threats. Although participants raised these and other issues, they were optimistic, overall, about the development and use of quantum technologies, and they were reassured by the fact that identified risks could be mitigated through legal and regulatory frameworks. They also expressed hope that these technologies would be used for the public good rather than to increase private profit (EPSRC, n.d.).

Researchers have developed a set of principles to guide RRI for quantum technologies

In 2023, an interdisciplinary group of researchers developed the concept of Responsible Quantum Technology (RQT) and a set of principles to advance responsible quantum innovation (Box 7.3). These principles incorporate the consideration of ethical, legal, social, and policy implications (Quantum ELSPI; see Chapters 4 and 5) into quantum R&D while responding to key RRI dimensions (Kop *et al.*, 2023). The resulting framework aims to safeguard against the risks presented by quantum technologies, ensure broad participation of different stakeholders in the innovation process, and advance innovation. RQT may be used as a foundation for a range of policies, from voluntary commitments and self-regulatory measures to binding laws and regulations (Kop *et al.*, 2023).

Box 7.3 Proposed Principles for RQT

1. Consider information security as an integral part of [quantum technologies] QT, addressing security threats;
2. Proactively anticipate the malicious use of quantum applications, addressing risks of dual use;
3. Seek international collaboration based on shared values, addressing a winner-takes-all dynamic;
4. Consider our planet as the sociotechnical environment in which QT should function, engaging states;
5. Be as open as possible, and as closed as necessary, engaging institutions;
6. Pursue diverse quantum R&D communities in terms of disciplines and people, engaging people;
7. Link quantum R&D explicitly to desirable social goals, advancing society;
8. Actively stimulate sustainable, cross-disciplinary innovation, advancing technology;
9. Create an ecosystem to learn about the possible uses and consequences of QT applications, advancing our understanding of Responsible QT;
10. Facilitate dialogues with stakeholders to better envision possible quantum futures, advancing our collective thinking and education about QT and its impact.

(Kop *et al.*, 2023)

Public outreach and education programs can help counter misinformation and stimulate adoption

As noted in Chapter 4, hype and misinformation may stifle the adoption of quantum technologies by end-users. Given the public controversies surrounding genetically modified organisms (GMOs) and other technological advances, the scientific community should be candid about quantum knowledge gaps and develop data-informed knowledge mobilization strategies that can mitigate hype and prevent potential "quantum phobia" (Inglesant *et al.*, 2016; Ezratty, 2022). Several strategies used to prevent hype about scientific research could prove useful for quantum research, as well. Effective interventions are based on the premise that communicating scientific uncertainty reduces the consumption of misinformation. Therefore, strategies for building trust and increasing credibility include documenting and flagging scientific uncertainty, explaining its scientific value, and describing its potential impacts on results (Jensen *et al.*, 2011; Ratcliff *et al.*, 2018; Flemming *et al.*, 2020).

To mitigate the negative impacts of quantum hype, Ezratty (2022) argues for greater transparency in quantum research and innovation through mechanisms such as (i) government agencies and research organizations creating and publishing progress reviews in collaboration with independent expert bodies, (ii) clearly describing the existing scientific and engineering challenges that must be overcome before quantum technologies can be commercialized, (iii) more accurately tracking and reporting on technological maturity levels for different quantum technologies, and (iv) the widescale adoption of broadly accepted third-party benchmarks that would allow for performance comparisons among different types of quantum computers.

Public education and outreach programs can help demystify quantum mechanics and address legitimate public concerns about the impacts of quantum technologies. Such initiatives are intended for people of different ages and socioeconomic backgrounds and can be sponsored by private companies, universities, and government departments and agencies (Seskir *et al.*, 2023). For example, the E.U. Quantum Flagship initiative develops tools for secondary, higher, and continued education, as well as public outreach (QTEdu, n.d.-a). In the United States, the National Q-12 Education Partnership — spearheaded by the National Science Foundation and the White House Office of Science and Technology Policy — relies on a network comprising industry, professional societies, and educators to promote early engagement with quantum science and technology among middle and high school students (Q-12 Partnership, n.d.).

In Canada, some researchers organize public outreach campaigns on quantum physics and technologies; for example, the Institute for Quantum Computing at the University of Waterloo has several programs on quantum information science and technology for high school and undergraduate students, and for high school teachers (IQC, n.d.-a). Similarly, Université de Sherbrooke's Institut quantique works to demystify quantum physics for high school and college students (IQ, n.d.). Other outreach approaches include interactive textbooks linked to publicly accessible hardware and open-source software (Wootton *et al.*, 2020) and community-based workshops (some of which focus on the mathematics of quantum computing while leaving out physics concepts) (Salehi *et al.*, 2022). All of these approaches are based on the premise that utilizing quantum technologies does not require an advanced knowledge of physics (Seskir *et al.*, 2023).

There are opportunities for implementing RRI in Canada

In Canada, RRI is an approach that remains the domain of fragmented research collectives and scholars interested in this field (Matthews *et al.*, 2021). Nonetheless, an emphasis on the responsible and ethical use of quantum technologies in the public interest could set Canada's approach apart from that of other countries and help it attract international talent. An RRI approach to quantum technologies could draw on lessons from AI and, in particular, the Treasury Board of Canada ADM Directive, which incorporated the societal impacts of AI into its risk-assessment process (GC, 2023d). Implementing RRI in Canada means creating training programs on quantum-related social issues for students in physics, engineering, and the natural and social sciences. Following the lead of research funding agencies across the world, the Social Sciences and Humanities Research Council (SSHRC) is well positioned to fund research and training programs in Quantum ELSPI (ISED, 2022d). Ultimately, incorporating RRI into the research and training process could diversify the workforce and promote the social acceptance of quantum technologies.

7.2 Panel Reflections

Quantum technologies include a wide range of devices and techniques, most of which are still at least several years away from reaching market. However, it is widely believed that commercially available quantum technologies have the potential to revolutionize many industries; as of 2023, quantum-classical hybrids are beginning to be adopted by a handful of users. During the panel's discussions, it became clear that it is difficult to quantify the extent to which different industries will be affected, as evidenced by the wide range of market value projections. In addition, as noted in Section 2.3, nearly all available estimates of the economic benefits of adopting quantum technologies focus on quantum computing, with no estimates of the value created by the adoption of quantum sensing or communications.

Sensing technologies are perhaps the closest to adoption, but some of them present privacy risks. Computing currently receives the most attention but is far from market-ready. However, a fault-tolerant quantum computer poses a serious global threat — it is likely such a technology could undermine most modern encryption. National security and security for private companies depend on the development and adoption of QRC, which, notably, does not require quantum technology to implement. The panel stresses that the failure to adopt QRC by governments and industries could be devastating. More immediately, data collected today could be stored and accessed at a later date using quantum decryption techniques.

Quantum technologies are being recognized globally as critical investments, inspiring many countries to commit millions if not billions of dollars to their development. The panel notes that these substantial investments are necessary, as quantum technology research can be slow and expensive, with much of the equipment and raw materials needing to be imported from specific suppliers (some of which are the only option). Canada cannot mine, manufacture, or otherwise create every input along any given quantum product's supply chain. As such, it is crucial that it cultivate robust and reliable international collaborations to supplement the points of the quantum value chain Canadian companies cannot fulfill, while also providing larger and additional export markets for domestic quantum companies.

The panel believes it is unlikely Canada can excel in all areas of quantum R&D and commercialization, but it could determine how to best specialize to stand out globally. However, regardless of whether or not Canada becomes a leader in the development and production of quantum technologies, domestic industries will need to adopt these technologies if they wish to remain globally competitive

— as will governments hoping to ensure national and economic security, public safety, and the integrity of infrastructure that provides key public services.

In 2023, Canada published its *National Quantum Strategy* (NQS). While the NQS is a good starting point for developing a domestic quantum ecosystem, the panel believes promising initiatives remain underfunded, especially compared to jurisdictions that have committed more significant amounts. To avoid falling behind, Canada could invest further in quantum technologies. To date, the majority of government support in Canada has focused on development and production; funding programs tend to support fundamental research and the creation of SMEs and start-ups, many of which have either not brought products to market or left Canada. The NQS largely focuses on supply-side initiatives with less support for stimulating diffusion and adoption. Although there is some spotlight on adopting users and sectors — such as the proposed roadmapping process — jurisdictions leading in the quantum space (e.g., China, United States) employ comprehensive technology adoption strategies for both the public and private sectors.

In the panel's view, the NQS does not pay sufficient attention to ELSPI related to the adoption of quantum technologies. As noted above, some quantum sensors could exacerbate surveillance concerns, and quantum computers could threaten digital encryption and worsen individual and collective discrimination. These capabilities complicate the application, interpretation, and enforcement of Canada's privacy and data protection laws. In addition, there is the challenge of ensuring equitable and broad access to quantum technologies across Canada as they become available. This vulnerability is aggravated by the fact that big technology companies can exploit their market power to dictate the terms and conditions of access; moreover, the application and enforcement of Canada's IP and competition law may favour major market players. Finally, because quantum science is conceptually challenging, quantum technologies are likewise difficult to understand and can be shrouded in mystery or overhyped.

Many strategies could help address these challenges and stimulate the adoption of quantum technologies. These include public-private co-operation (e.g., government procurement and other specialized programs, public-private partnerships), regulation, pro-competition oversight and policies, industry-led initiatives, and building a diverse quantum workforce. These strategies could allow different orders of government to steer the direction of quantum innovation and use innovation policy as an instrument to address ELSPI and geopolitical issues raised by quantum technologies. The panel also emphasizes the value of different types of training, including technical, development-side qualifications; application-based, demand-side training; and general training for senior executives, so they can better assess how and when their organizations should adopt quantum technologies. To increase societal trust and transparency, and to combat misinformation and sensationalism, public outreach initiatives could raise awareness of what quantum technologies can and cannot do — such initiatives may boost public trust, a pre-condition for the broad adoption of quantum technologies.

The panel also noted a lack of reproducible, empirical data on a variety of topics, which makes targeted planning and decision-making difficult. These include:

- demographics of HQP in Canada;
- demand for HQP in industry, including areas of expertise and level of training desired; and
- technology transfer strategies, and the importance of certain metrics, such as patents.

As well, there is general uncertainty about the exact capabilities, costs, technological maturity, and availability timelines of quantum technologies, which has led to key knowledge gaps. Addressing these gaps will help inform government decisions about which types of programming to offer in the future, and assist policy-makers in understanding how Canada can specialize and differentiate itself in the global quantum market.

It is vitally important that Canada prepare for the emergence and widespread availability of quantum technologies. Over the long term, these technologies are poised to have a broad range of social and economic impacts, many of which may not be foreseeable (in much the same way that it was difficult to foresee the ways in which transistors and classical computers would impact every aspect of society). Importantly, however, that preparation goes beyond ensuring Canada has the enabling conditions in place to provide broad access to, and market readiness for, quantum technologies; preparation is also key to ensuring the long-term sustainability of a domestic quantum industry and manufacturing base that can support and maintain adoption by organizations in Canada and around the world. This will require an innovation strategy that prioritizes developing and retaining quantum IP and talent in Canada.

Key Terms

Any technology that uses the principles of quantum science, including quantum computers, medical devices, sensors, secure communications, and atomic clocks, may be considered a *quantum technology. First-generation* quantum technologies are generally understood to be those that take advantage of quantum-based behaviours (e.g., semiconductors, lasers, MRI). *Second-generation* technologies are those that manipulate and control quantum dynamics. For example, *quantum computing* is considered second-generation because it requires arranging and controlling the flow of quantum information. Discussing quantum technologies requires a level of understanding of quantum science; therefore, most discourse about quantum technologies is undertaken by experts in the field using language that can be hard for non-experts to follow. This list of key terms provides non-technical and non-rigorous descriptions of some of the quantum-specific concepts found in the report. For a technical glossary, the reader is encouraged to refer to Ezratty (2021) and Hoofnagle & Garfinkel (2021).

Entanglement is a quantum phenomenon whereby the states of two or more quantum objects are superposed. Measuring the two-object quantum state in complementary bases reveals correlated (but random) values. Entangling qubits through quantum gates is a new resource not available to today's classical computers. Entanglement is also used in quantum cryptography and telecommunications systems that rely on quantum key distribution (QKD).

Noisy intermediate-scale quantum (NISQ) devices are gate-based quantum computers whose decoherence — sometimes referred to as *noise* — is not mitigated or corrected. NISQ devices can reach hundreds of qubits.

Quantum advantage describes the stage when quantum computers can solve certain problems cheaper, faster, and more accurately than classical computers, or solve problems that classical computers are unable to feasibly solve. However, the details of what specific benchmarks are needed to demonstrate quantum advantage are hotly debated.

Quantum algorithm describes an algorithm comprising input, output, and procedure, with the procedure expressed as a sequence of instructions native to a quantum computer and implemented by quantum circuits.

Quantum annealer refers to a type of quantum processor that executes a heuristic known as quantum annealing to find solutions to hard optimization problems. Quantum dynamics drive the system toward its lowest energy states that are aligned with the optimal solutions of a desired objective function. Quantum annealers are intended to solve certain optimization problems better than classical methods by simultaneously exploring many possible outcomes via quantum effects, such as superposition and entanglement.

Quantum circuit refers to a sequence of inputs, logic gates, measurements, and qubits used to implement quantum algorithms.

Quantum computing is a computing paradigm that relies on storing and manipulating quantum information.

Quantum computing as a service (QCaaS) makes off-site quantum computers, both actual and simulated, available remotely (i.e., through the cloud).

Quantum error correction is a technique for encoding, processing, and then decoding quantum information to protect against errors that arise during computation, including decoherence. Decoherence is the process of losing quantum coherence, which is the characteristic of superposing different states of the system. Decoherence often occurs due to interactions between quantum objects and their environment. Coherence time is the duration over which quantum objects remain in superpositions of states, after which decoherence is said to occur.

Quantum gate refers to the quantum analogue to classical logic gates (which form the basis of modern computing algorithms).

Quantum internet is a term used to describe a network that incorporates quantum information-sharing among quantum devices such as computers and sensors.

Quantum key distribution (QKD) is a suite of secure protocols, leveraging the capability to transmit quantum information, for establishing symmetrical encryption keys. It is implemented with photonic transmission, typically in free space via satellites or through optical fibres. The randomness of these keys is enabled by the randomness inherent in quantum measurements; security against eavesdropping is due to interception being detectable.

Quantum machine learning (QML) broadly refers to the integration of quantum computing with machine learning. This can encompass a variety of different approaches and techniques, and typically involves classical-quantum hybrid computing.

Quantum readiness is the ability of a business to adopt quantum-enabled processes to gain a competitive advantage once mature quantum technologies become available.

Quantum-resistant cryptography (QRC) refers to algorithms thought to be secure against attacks by quantum computers. It is also known as post-quantum cryptography (PQC) and quantum-safe cryptography (QSC). There are two main types: one based on classical codes resistant to quantum computers and one based on using quantum information to protect against attacks.

Quantum simulator is a term given to analogue quantum computers that are capable of reliably simulating quantum systems with application to quantum materials. Alternatively, the term may be used for classical numerical simulation of quantum computing.

Quantum state refers to the mathematical description of the quantum system that can be used to predict statistical properties of measurements.

Qubits are the quantum equivalent of classical computing *bits* that encode information in its quantum state. Whereas a classical bit can take on one of two values (0 or 1), a qubit can be in a superposition of states. It is the basic building block of most quantum computers and quantum communications. Various types of qubits are realized for different materials and technologies.

RSA encryption is a widely used asymmetric encryption system (named for Ron Rivest, Adi Shamir, and Leonard Adleman) based on the difficulty of factoring a public key formed by multiplying two large prime numbers. This factorization is difficult to do classically but can be efficiently solved using Shor's algorithm. Breaking RSA and similar encryption schemes could be devastating for national security, business security, and individual data privacy.

Shor's algorithm is a quantum algorithm for integer factorization, which could be used by a quantum computer to break nearly all existing symmetric-key encryption protocols in use today, including RSA encryption.

Superposition is the quantum property that assumes an object's quantum state can be in a coherent combination of states at the same time.

Universal quantum computer refers to a quantum computer that can efficiently simulate any purpose-built quantum computer.

Appendix A NAICS Codes Corresponding to Figures in Chapter 2

Table A.1 NAICS Codes Corresponding to Figure 2.2

Sector	NAICS Code	NAICS Description
Agriculture	11	Agriculture, forestry, fishing, and hunting
Automotive and Aerospace Manufacturing	336	Transportation equipment manufacturing
Chemistry and Materials Science	3251-3253, 3255, 3256, 3259	All other chemical manufacturing
Finance	52	Finance and insurance excluding monetary authorities
Mining and Oil & Gas	21	Mining, quarrying, and oil and gas extraction
Pharmaceuticals	3254	Pharmaceutical and medicine manufacturing
Telecommunications	517	Telecommunications
Transportation	48, 49	Transportation and warehousing

Table A.2 NAICS Codes Corresponding to Figure 2.3

Sector	NAICS Code	NAICS Description
Agriculture	111, 1121-1124, 1129, 1151, 1152	Agriculture (except aquaculture) and support activities for crop production and animal production
Automotive and Aerospace Manufacturing	3361-3363, 3364	Motor vehicle, motor vehicle body and trailer and motor vehicle parts manufacturing / Aerospace product and parts manufacturing
Chemistry and Materials Science	3251-3253, 3255, 3256, 3259	All other chemical manufacturing
Energy	2211	Electric power generation, transmission and distribution
Finance	52	Finance and insurance
Healthcare	62	Health care and social assistance
Mining and Oil & Gas	21	Mining, quarrying, and oil and gas extraction
Pharmaceuticals	3254	Pharmaceutical and medicine manufacturing
Telecommunications	517, 518	Telecommunications and data processing, hosting and related services
Transportation	48, 49	Transportation and warehousing

Appendix B Applications of Quantum Technologies in Adopting Sectors

Agriculture

Computing

In the agricultural sector, quantum simulation offers the possibility of a new approach to nitrogen fixation — the process of converting atmospheric nitrogen into organic compounds (e.g., ammonia) used to create fertilizers essential to modern agriculture (Crane *et al.*, 2017; Denver, 2020). Currently, industrial processes used for nitrogen fixation (e.g., the Haber-Bosch process) require significant quantities of energy, accounting for as much as 5% of the total global consumption of natural gas (Crane *et al.*, 2017). They also produce significant quantities of greenhouse gases as a by-product — as much as 2–3% of global CO_2 emissions (Quantum Flagship, n.d).

Quantum simulation may allow for the discovery of more energy-efficient production methods by modelling the process by which bacteria fix nitrogen (Crane *et al.*, 2017). Specifically, identifying catalysts could reduce the amount of energy required (by reducing the amount of heat and pressure needed) and the cost of ammonia production (Denver, 2020). While quantum computers cannot yet simulate nitrogen fixation processes in sufficient detail for fertilizer production (Crane *et al.*, 2017; Reiher *et al.*, 2017), some sources suggest it may occur before 2030 (IBM, n.d.-a). Moreover, researchers have described in detail how such processes could be implemented by a hybrid quantum/classical architecture once quantum computing hardware is sufficiently advanced (Reiher *et al.*, 2017). However, there is currently little evidence of quantum advantage in this area (Lee *et al.*, 2023).

Quantum computing may also have applications in predictive agriculture. The Spanish National Research Council is undertaking a project in collaboration with industry partners to use quantum machine learning (QML) to more accurately predict crop yields through the analysis of satellite images, combined with weather, risk, and multi-spectral imaging data, as well as other sources (CSIC, 2022).

Sensing

Some have suggested that quantum gravimeters based on atomic interferometry could help with precision agriculture by detecting soil conditions, such as level of compactification and distinguishing between dry and saturated soil (Stray *et al.*, 2022).

Chemistry and Materials Science

Computing

Quantum computing has various applications in chemistry and materials science, including simulations of properties of molecules and materials that, in many cases, are best explained applying quantum mechanics (Bauer *et al.*, 2019). Indeed, simulation of quantum systems is the most promising application in the chemical sector and could be used to help researchers better understand mechanisms of chemical reactions and design better catalysts (Budde & Volz, 2019). A 2019 workshop examining the use of quantum computing in chemistry and materials science identified several simulation challenges in "quantum chemistry, quantum molecular spectroscopy and chemical quantum dynamics, correlated electronic structure in materials, and dynamical quantum effects in materials" (Bauer *et al.*, 2019; Gunashekar *et al.*, 2022). Quantum computers offer potential solutions to problems in these domains that are more precise than methods that rely on classical computers (Ho *et al.*, 2018). However, these use cases are unlikely to become widely available in the near term (Biondi *et al.*, 2021). Quantum computers may be applied to optimization problems in the chemicals sector, such as optimizing production processes and supply chains (Budde & Volz, 2019).

In materials science, quantum computers can potentially be used to automate the materials discovery process and enable the exploration of materials design space in ways that classical computers cannot, thereby allowing for the development of new materials with a wide variety of applications (Kitai *et al.*, 2020). They have also been used for simulating materials in order to allow greater understanding of magnetic structures and properties (Rosenthal, 2021). Once again, however, the application of quantum computers to these types of simulation problems is unlikely to be commercially viable in the near or medium terms (Biondi *et al.*, 2021).

Sensing

Quantum sensors have applications in chemistry and materials science. For example, sensors based on nitrogen-vacancy (NV) centre diamonds have been used for nuclear magnetic resonance (NMR) spectroscopy (Allert *et al.*, 2022; Liu *et al.*, 2022), an important tool for chemical and structural analysis (Liu *et al.*, 2022). Previous NMR spectroscopy techniques were limited to larger, macroscopic scales, whereas NV centres can enable NMR spectroscopy at the level of single molecules and atoms (Allert *et al.*, 2022).

Defence / Intelligence

Computing

A variety of applications for quantum computing exist in the defence sector, including optimization problems, QML, and simulations. Optimization problems in this sector that could be addressed by quantum computers include "logistics for overseas operations and deployment, mission planning, war games, systems validation and verification, new vehicles' design and their attributes such as stealth or agility" (Krelina, 2021). QML may be used to support military decision-making, mission-planning, cyber operations, and targeting (Sayler, 2021; Krelina, 2021). Quantum computers are likely to play a role in processing and analyzing intelligence, surveillance, and reconnaissance data, while quantum simulation may also be used to develop chemical and biological weapons and defences, or have materials science applications such as designing materials for camouflage, stealth, armour, or high-temperature-tolerant materials. The use of quantum computers for optimization problems, QML applications, and quantum simulation are all expected to occur in the near or medium terms (Krelina, 2021).

Sensing

There is a great deal of interest in quantum sensing for military applications; indeed, Canada's DND has prioritized quantum sensors as the first pillar of its strategic plan (DND & CAF, 2021). Quantum sensors may be used to develop inertial navigation systems that provide more accurate positioning and allow for navigation when GPS is jammed or unavailable (e.g., in underwater or underground situations), as well as inertial navigation system in guided missiles (Neumann *et al.*, 2021; Parker, 2021). Submarines may be among the earliest adopters of quantum inertial navigation (Krelina, 2021).

Quantum sensors are also important for ISTAR (intelligence, surveillance, target acquisition, and reconnaissance); they can be placed on individual land, sea, and aerial vehicles (including drones), as well as satellites in low Earth orbit (Krelina, 2021). For example, quantum magnetometers and gravimeters may be used to detect camouflaged vehicles, aircraft, or submarines; search for fleets of ships from space-based satellites; and detect underground structures (e.g., bunkers) and buried objects (e.g., landmines, underwater mines) (Krelina, 2021).

Finally, quantum radar (and LIDAR) "could be a powerfully disruptive technology that could change the rules of modern warfare" (Krelina, 2021) by allowing for improved detection and identification of targets, while being resistant to interference and difficult to detect. In addition, classical radar may be enhanced with atomic or quantum clocks. Some sources have suggested that quantum radar faces a wide range of technical challenges that make it unlikely to become available for the foreseeable future (Krelina, 2021); however, Canada's DND has prioritized building and field-testing quantum-enhanced radar and LIDAR by 2030 (DND & CAF, 2023).

Communications

Quantum communications networks have important defence applications, such as allowing for secure communications among ground, air, marine, and space-based assets (Krelina, 2021). Quantum cryptography systems could also be developed to allow position-based quantum encryption in which information can only be accessed from a particular geographical location, such as military bases (Neumann *et al.*, 2021). In addition, quantum antennas could have applications for electronic warfare by allowing signal interception with a very small-sized antenna, even at low-frequency wavelengths (DND & CAF, 2021; Krelina, 2021).

The United States Air Force has rejected QKD on the grounds that there is no proven need for QKD technology that makes systems more complex while offering "little advantage over the best classical alternatives" (USAF, n.d.). However, QRC is vital for defence applications. Indeed, both foreign and domestic intelligence agencies may be collecting intercepted encrypted data to be decrypted at a later date, once quantum computers are available (Krelina, 2021). Canada's DND has prioritized demonstrating "a quantum algorithm solving a defence and/or security problem" by 2030 (DND & CAF, 2023).

Energy

Computing

There are myriad applications for quantum computing in the energy sector. Quantum computers may be applied to energy systems optimization problems, such as allocating the distribution of energy infrastructure, while minimizing operating and energy transportation costs, given constraints such as resource availability, electric grid load, and energy demand (Ajagekar & You, 2019). In addition, quantum computing may help address challenges achieving sustainable energy by providing simulations of materials and systems at the atomic scale, which could lead to the development of a variety of technologies, including improved biofuels, solar energy conversion, nuclear fusion reactor walls, and the design of materials to improve carbon capture and storage (Dieterich & Carter, 2017; Total Energies, 2020).

Sensing

There are multiple potential applications for quantum sensors in the energy sector beyond oil and gas extraction. Sensors based on NV centres in diamonds can be used to monitor the integrity of energy infrastructure, such as detecting leaks in pipelines, and the temperature and stress/strain on power lines, towers, and transformers during electricity transmission (Crawford *et al.*, 2021). Quantum sensors may also play a role in monitoring carbon capture and storage, such as using quantum LIDAR to detect CO_2 emissions and leaks. Finally, sensors such as superconducting quantum interference devices (SQUIDs) and atomic interferometers may be applied in monitoring nuclear energy plants (Crawford *et al.*, 2021).

Finance

Computing

The financial sector has demonstrated significant interest in quantum computing. This may be due to the interesting overlap between quantum processes and finance. Indeed, "some well-known financial problems can be directly expressed in a quantum-mechanical form. ... Even the entire financial market can be modeled as a quantum process, where quantities that are important to finance, such as the covariance matrix, emerge naturally" (Orus *et al.*, 2019).

Many of the problems in finance that could benefit from quantum computers are optimization problems that are extremely difficult, if not impossible, to solve using a classical computer (Orus *et al.*, 2019; Egger *et al.*, 2020). These typically focus on maximizing the return of a portfolio by identifying optimal trading trajectories and arbitrage opportunities (Rosenberg *et al.*, 2016; Rebentrost & Lloyd, 2018; Orus *et al.*, 2019). However, the advantages offered by quantum optimization to the finance sector in the near term may be speculative (Biondi *et al.*, 2021).

QML may be useful in the financial sector for facilitating the identification of patterns in financial data. This could be used to determine the optimal feature selection in credit risk ratings (i.e., using historical data to gauge what features can best predict creditworthiness), detect fraud, and manage uncertainty around the future evolution of asset prices and risk (Orus *et al.*, 2019; Egger *et al.*, 2020). Quantum computers may also significantly speed up simulations for finance applications, such as those using Monte Carlo methods of computation, which analyze large, complex systems by simulating sources of uncertainty. Such methods may be used for pricing derivatives and estimating risk (Orus *et al.*, 2019; Egger *et al.*, 2020). In addition, it has been suggested that a topological quantum computer could simulate market behaviour and help predict future market trajectories (Racorean, 2014). However, many of these applications are unlikely to become available in the near or medium terms, although using quantum computers for optimization problems may occur somewhat sooner (Biondi *et al.*, 2021).

Communications

Quantum communications and cryptography are of great interest to the financial sector. In addition to ensuring that financial transactions are protected by QRC (IDQ, 2018), the finance sector could be among the first adopters of QKD (QDNL, 2020). There is also significant interest in how quantum cryptography might affect blockchain-based cryptocurrencies. Kearney and Perez-Delgado (2021) analyzed several such technologies and found they were all at least partially vulnerable to quantum attack. However, there are several reasons such attacks would be difficult to implement and limited in what they could achieve (Huang, 2020). Furthermore, there are ongoing initiatives to make such technologies resistant to quantum attack.

Healthcare

Computing

In the healthcare setting, quantum computing may be used to support clinical decision-making by offering predictions and recommendations based on patient data (Sahner & Williams, 2021). One of the most promising implementations of quantum computing in the healthcare sector is QML, due to the large (and fast-growing) volumes of health-related data (IBM, 2020). QML may be used for diagnostic assistance; for example, it could analyze medical scans such as CT, MRI, and X-ray images (Acar & Yilmaz, 2020; IBM, 2020). QML may also help improve precision medicine by allowing for increased accuracy in risk predictions for patients, predictions of the effectiveness of drugs at a cellular level, and more precise and personalized diagnoses and treatments. Furthermore, it may help improve single-cell diagnostic methods and lead to the discovery and identification of biomarkers through the analysis of complex datasets (IBM, 2020).

However, widespread adoption of QML for personalized medicine is unlikely to occur in the near or medium terms (Biondi *et al.*, 2021). In the nearer term, the use of quantum computing for radiotherapy optimization is more likely, using quantum computers (Nazareth & Spaans, 2015) or quantum-inspired algorithms run on classical computers (Pakela *et al.*, 2020); in the medium-to-long term, QML may be used for this purpose (Cavinato *et al.*, 2020; Niraula *et al.*, 2021).

Sensing

Quantum sensors known as *optically pumped magnetometers* (OPMs) have allowed researchers to create the first wearable magnetoencephalography (MEG) systems; these will improve the accuracy, flexibility, adaptability, and portability of MEG devices and reduce costs (Aslam *et al.*, 2023; UKQTHST, n.d.-a). OPM-MEG offers better spatial and temporal resolution than current MEG based on SQUIDs, which, unlike OPM-MEG, require magnetically shielded rooms and cryogenic operating conditions (Coussens *et al.*, 2021; Gialopsou *et al.*, 2021). Currently, OPM-MEGs are being deployed at SickKids in Toronto for autism research (UKQTHST, 2021a) and in the United Kingdom for detecting brain diseases (UKQTHST, 2021b). In addition, OPMs may also be used for other health-related sensing applications, such as cardiology (Jensen *et al.*, 2018; Aslam *et al.*, 2023). They are likely to become more widely available in the near term (i.e., before 2030).

Quantum sensors based on NV centres also have applications in healthcare. For example, they have been used to detect magnetic nanoparticles in diagnostic applications by distinguishing between healthy cells and cancer cells (Glenn *et al.*, 2015). This approach has potential advantages over approaches that use fluorescent markers (Aslam *et al.*, 2023). Additionally, magnetic microscopy using NV centres has been used to investigate the biomarkers of malaria (Fescenko *et al.*, 2019) and identify specific proteins in patients hospitalized with COVID-19 (Atallah *et al.*, 2022). NV centres have also been used to measure the activity of single neurons, which could complement and improve the use of MEG (Barry *et al.*, 2016). NV centres may also have applications in NMR spectroscopy, where they could increase spectral resolution and improve spatial resolution limitations from milli- to nanometre scale (Aslam *et al.*, 2023). This would allow for easier analysis of samples that are expensive or difficult to synthesize, and could enable "detailed studies of cell structure and function, with applications in metabolomics and disease diagnosis." NV centres in nanodiamonds may also be used for thermometry, allowing for the investigation of "temperature-related biological phenomena in cells and small organisms," and provide sensing at a smaller scale, with greater stability compared to conventional temperature probes (Aslam *et al.*, 2023).

Communications

QRC is important in the healthcare sector due to the potential risks to patient data (IDQ, 2022). It could be used to ensure the secure transfer of medical images (Alowolodu *et al.*, 2018), for secure communication with wireless body sensors (Devi & Kalaivani, 2021), and for other Internet of Things-based healthcare applications. However, while QRC is likely to become more widely available in the near term, its adoption in Canada's health sector may take some time, given that a significant amount of health data in Canada are still transmitted by fax machine (IPC, 2022; CBC News, 2023).

Manufacturing

Quantum technologies are likely to impact manufacturing across a wide range of different industries and sectors, many of which are described elsewhere in Appendix B. As Doyletech (2020) states:

> *While any single manufacturing sector may not warrant, or be able to support, significant uptake of quantum technologies, as a group the manufacturing sector holds the possibility to greatly impact the Canadian economy through the use of quantum technologies.*

Computing

Quantum computing in manufacturing is likely to be used for applications such as quantum simulation for product engineering, design, and materials discovery, and in the optimization of supply chains, routing and logistics, production processes, and production scheduling (IBM, 2019; Doyletech Corporation, 2020; QUTAC *et al.*, 2021; Capgemini, 2022). This will likely occur in a range of diverse sectors, including automotive and aerospace, chemistry and materials science, sustainable infrastructure (e.g., solar panels), and pharmaceuticals (QUTAC *et al.*, 2021; Capgemini, 2022). In addition, researchers are currently exploring general-use applications of quantum computing for industrial manufacturing, such as demonstrating how quantum annealing can optimize factory layout planning (Klar *et al.*, 2022), and how quantum computing can be integrated with traditional computer-aided design (Wille *et al.*, 2018).

Another important impact of quantum computing on manufacturing is the need to manufacture quantum technology hardware and components. In many cases, specialized nanofabrication and microfabrication techniques and facilities are required to manufacture quantum technologies (Laucht *et al.*, 2021) (Section 3.3). Developing scalable manufacturing processes for qubits is an ongoing area of research and development (Gonzalez-Zalba *et al.*, 2019; Zwerver *et al.*, 2022). Additionally, quantum machine learning may one day be used to improve the design and control of quantum computers themselves, thereby enabling "a virtuous cycle of innovation similar to that which occurred in classical computing, wherein each generation of processors is then leveraged to design the next-generation processors" (Biamonte *et al.*, 2017).

Mining and Oil & Gas

Computing

Quantum computing may be applied in the mining sector to optimize operations and processes, such as the use and distribution of energy and water, as well as to simulate complex chemical reactions. This can help reduce the environmental footprint of mining operations, along with the associated liabilities and closure costs. Moreover, QML may be used to increase automation in mining operations (NRC, 2017a). Quantum computers have also been applied to optimizing the process and design of open-pit mining, with the goal of minimizing costs and maximizing efficiency, given the relevant geological, engineering, and environmental constraints (Hindy *et al.*, 2021).

Sensing

One of the primary benefits of quantum sensors in the extractives sector is their ability to detect and identify underground deposits without drilling or excavation, via the use of quantum gravimeters and magnetometers that can provide far greater accuracy than current sensing technology (NRC, 2017a; Crawford *et al.*, 2021). In addition, the high degree of precision offered by atomic clocks could enhance sensors for more accurate underwater exploration and terrain mapping (NRC, 2017a; Crawford *et al.*, 2021). Quantum magnetometers may also be used to analyze geological samples with an extremely high degree of precision and help autonomous vehicles navigate in mining environments. Sensors utilizing *fiber Bragg gratings* may be used to monitor the structural health of tailings ponds (NRC, 2017a). Finally, quantum imaging based on nonlinear optical methods — known in the mineral sector as *geophotonics* (Andreana & Stolow, 2014) — has a variety of potential applications in the mining industry, including improving the recovery of target elements from extract materials (NRC, 2017a). Quantum sensing in the mining industry can also help to identify deposits of critical minerals and mitigate the environmental impacts of extraction more easily (ISED, 2023d).

Pharmaceuticals

Computing

Quantum computing is expected to significantly impact the biopharma sector, with use cases across R&D stages. It has been described as one of the most promising (and financially valuable) sectors for quantum advantage, along with chemistry and materials science, with quantum simulation showing particular promise (Langione *et al.*, 2019b). Quantum computers may be used to optimize the drug design and discovery process, as well as simulate the effects of different compounds on their biological targets; this could reduce the number and costs of clinical trials (Langione *et al.*, 2019a), as well as the risks to patients. However, drug discovery is expected to be a longer-term goal in this sector that will require further technological maturity. Quantum computers have also been applied to problems such as mRNA codon optimization (Fox *et al.*, 2021), predicting protein folding (Robert *et al.*, 2021), and designing peptides to create proteins (Mulligan *et al.*, 2019), all of which could help researchers understand diseases and create therapeutics to treat them. However, these applications are in the very early stages.

Sensing

In addition to their applications in chemistry, materials science, and healthcare, NV centres for NMR spectroscopy have applications in the pharmaceutical sector. For example, they could enable the study of the structure and dynamics of cell membrane proteins, which are frequently targeted by drugs, thereby aiding in drug discovery (Aslam *et al.*, 2023).

Scientific Research

Computing

Quantum computing has a variety of applications in fundamental scientific research, particularly in physics. For example, it can be used to simulate the effects of particle collisions that are quantum mechanical in nature and difficult to describe using classical computers (Nachman *et al.*, 2021). In addition, QML has been used to classify Higgs bosons at a level comparable to current methods, with advantages over classical machine learning when applied to smaller training datasets (Mott *et al.*, 2017). Indeed, the European Organization for Nuclear Research (CERN) has developed a quantum technology strategy and roadmap that, among other goals, seeks to use quantum computers to analyze data from supercolliders and potentially design new particle detectors (Bilton *et al.*, 2021).

Importantly, quantum computers have applications in a wide range of scientific disciplines beyond physics; their use in chemistry, materials science, and the life sciences is described elsewhere in Appendix B. They have also been applied to inversion problems (roughly, calculating causes based on observed effects) in a variety of fields, including hydrology (O'Malley, 2018) and seismic geophysics (Souza *et al.*, 2022).

Sensing

Quantum sensors allow for extremely precise measurements and could be used to explore problems in a variety of physics subfields, including general relativity, cosmology, quantum mechanics, and physics beyond the Standard Model. Space-based quantum sensors for scientific research is also a significant area of interest (Alonso *et al.*, 2022).

Space

There are a wide variety of applications for space-based quantum technologies in several different sectors, including telecommunications, defence, and scientific research. These types of use cases are described in those respective sections. By contrast, this section focuses on uses for quantum technology in the space sector itself.

Computing

NASA has identified a variety of use cases for quantum computing, including diagnostics and fault management in complex engineering systems such as the International Space Station; optimizing mission planning for the best use of resources, such as time and power; and optimizing the timing of satellite observations, flight routes, and landing patterns (NASA, 2017).

Sensing

Space-based quantum radar may be useful for detecting near-Earth objects and debris that threaten spacecraft, satellites, or the Earth itself (Marco & Jeffrey, 2015). Atomic interferometers and atomic clocks deployed on satellites could be used to test theories about dark matter and dark energy, detect and precisely measure gravitational waves, and test quantum entanglement over astronomical distances (Alonso *et al.*, 2022). Beyond physics, space-based quantum sensing using atomic interferometers, gravimeters, and atomic clocks has applications in Earth observation, such as detecting large-scale changes in the planet (Alonso *et al.*, 2022). This can help improve climate modelling, as well as the monitoring of natural disasters, such as floods, earthquakes, and volcanic activity. It can also potentially help mitigate the impact of such events (UKQTHST, n.d.-d).

Communications

NASA is currently working on a project to test a laser-based quantum communications system onboard the International Space Station to transmit information from one location on Earth to another (Oberhaus, 2020).

Telecommunications

Computing

Quantum computing is being applied to optimization problems in the telecommunications industry, such as "the placement, power and frequency assignment of overlapping cells in 4G/5G mobile networks, the configurations of paths and wavelengths on land line fiber optics networks" (Ezratty, 2021), and the identification of optimal configurations for space-based satellites in order to maximize the coverage area (Bass *et al.*, 2018). Quantum computing has also been applied to problems in routing wireless traffic in multiple input / multiple output (MIMO) antenna arrays to support many users at the same time (Kim *et al.*, 2020). The use of quantum computing to address optimization problems in the telecommunications sector is likely to become more common in the near term.

Sensing

The telecommunications industry may eventually make use of quantum optical clocks to more accurately synchronize devices across a communications network, which would allow for new technologies that are not currently feasible, such as distributed MIMO and quantum networking (Martin *et al.*, 2021).

Communications

All modern communications — including the internet and mobile networks, as well as the infrastructure through which these are delivered — are protected by encryption. Therefore, new security measures such as QRC and QKD will need to be implemented in order to maintain existing security once fault-tolerant quantum computers become available (ATIS, 2022). Telecom operators may use QKD for both internal and external applications — that is, protecting the internal security of the network infrastructure (e.g., connections between data centres) and external user data traffic (Martin *et al.*, 2021). Ground-based QKD using fibre optics has been tested for telecommunications in a few jurisdictions, including the United States (Weissberger, 2020) and the United Kingdom (BT Group, 2020).

In addition, there is a great deal of interest in satellite-based secure communications systems using QKD, particularly since ground-based QKD faces technical challenges that limit its transmission distance (Jennewein *et al.*, 2014). As noted in Section 2.1.3, several experiments testing satellite-based QKD have already been undertaken such as the QEYSSat mission (IQC, n.d.-b). The telecommunications sector is expected to be among the earliest adopters of QKD.

Transportation and Logistics

Computing

Quantum computing has numerous applications for optimization problems in automotive, air, and maritime transport. In the air transportation sector, quantum computing and quantum-inspired algorithms have been applied to optimization problems such as gate assignments (Lobe & Stollenwer, 2019), assigning individual aircraft to specific sets of flights (Swayne, 2020; Vikstål *et al.*, 2020), and optimizing aircraft loading for passengers and cargo (Ezratty, 2021). In automotive transportation, quantum computing has been applied to optimizing traffic flow (Neukart *et al.*, 2017) and traffic signals (Inoue *et al.*, 2021). Similar applications were developed for maritime traffic routing (Harwood *et al.*, 2021) and port operations (TradeArabia, 2021; D-Wave, 2022).

Quantum computers also have important optimization applications in the logistics industry; they are expected to have transformative potential in this area in the near- to medium-term (DHL International, 2020) and will likely be used for dynamic route optimization — a problem that can be very difficult or even impossible for classical computers to feasibly solve. They may also be used to optimize the simultaneous packing of cargo and parcels, and for building more resilient supply chains through adaptive reallocation of assets in the event of disruptions (DHL International, 2020). More widespread availability of quantum computing for optimization problems in the transport sector is expected within the medium term.

The use of quantum computers for simulation also has applications in the transportation sector related to aerospace and automotive R&D and manufacturing, such as simulating vehicle stability, aerodynamics, and thermodynamics (Langione *et al.*, 2019b; Biondi *et al.*, 2021). For example, Airbus has used quantum computers for several purposes, including aircraft design (e.g., simulating fluid mechanics, differential equations, flight optimization) and optimizing cargo loading (Feldman, 2019); similarly, Rolls Royce has used quantum simulation of computational fluid dynamics for the purpose of jet engine design (NVIDIA, 2023). Furthermore, quantum computing may also help researchers develop better batteries for electric vehicles by simulating chemical processes and reactions, which will contribute to increased efficiency and reduced wear (Ho *et al.*, 2018; Biondi *et al.*, 2021; Rice *et al.*, 2021). However, more widespread use of quantum simulation in the transportation sector is unlikely to occur in the near- or medium-term.

Sensing

Quantum sensors may also have applications in the transportation sector by enhancing (or eventually replacing) existing navigation systems, such as global navigation satellite systems (GNSS) (UKQTHST, 2021c). New navigation systems based on quantum sensing could eventually be used to help autonomous vehicles navigate their environments (UKQTHST, n.d.-c). Similarly, quantum gravimeters and magnetometers could provide navigation systems for autonomous shipping and underwater vehicles that face frequent losses of satellite signal (UKQTHST, n.d.-b).

Communications

QRC may become an important issue in the automotive industry, as the RSA encryption typically used in vehicle electronic control units could be vulnerable to attacks by quantum computers (Wang & Stöttinger, 2020).

Appendix C Research Metrics Methodology

Research activity metrics — including overall research activity, growth in research activity, degree of international collaboration, and share of highly cited research — were derived from data collected from the Web of Science Core Collection database following the inclusion criteria from Parker *et al.* (2022). The Web of Science database is composed of peer-reviewed journals, books, and conference proceedings that are curated based on quality and influence (Clarivate, n.d.). A common search strategy was employed for each application (computing, communications, sensing) using its own set of key search terms (Table C.1). From here, entries were further winnowed by selecting for articles and conference proceedings (excluding review articles and books). Ideally, this would remove all entries that fall outside the domain of each application, leaving three sets of entries for each application that could be further refined by publication date, author affiliation details, and journal.

To quantify degree of international collaboration, entries were refined based on authors' country of affiliation. For any country, a subset of entries with at least one author affiliated with the chosen country were identified. From this subset, the number of entries with at least one co-author from any other country were recorded. This refinement strategy was also done for co-authors specifically affiliated with Russia or China.

A systematic approach to identifying highly influential research was employed using the total number of citations for a given entry as a metric (i.e., share of highly cited papers). Because older entries have had a longer time to be found, read, and cited, entries were only compared to each other within the year they were published. "Highly cited" for a given year was defined as entries in the 90th percentile when ranked by citation count (citations could occur in any year). This subset was refined further to isolate entries with at least one author affiliated with a specified country. For example, in 2016, 2.9% of the entries in the 90th percentile of citations relating to quantum communications (Communications subset) had at least one author with Canadian affiliation.

Table C.1 Search Terms Used to Identify Publications and Conference Proceedings in the Web of Science Core Collection Database According to Technology

Technology	Search Terms
Computing	“adiabatic quantum comput*”or “amplitude amplification”or “analog quantum simulation*”or “blind quantum comput*”or “boson sampling”or “bqp”or “bqp-complete”or “charge qubit*”or “circuit quantum electrodynamics”or “cluster state*”or “d-wave”or “delegated quantum comput*”or “deutsch-jozsa algorithm*”or “distributed quantum comput*”or “duality quantum comput*”or “durr-hoyer algorithm*”or “fault-tolerant quantum comput*”or “flux qubit*”or “geometric quantum comput*”or “grover algorithm*”or “grover's algorithm*”or “grover's quantum search algorithm*”or “hadamard gate*”or “hhl algorithm*”or “holonomic quantum comput*”or “linear optical quantum comput*”or “logical qubit*”or “measurement-based quantum comput*”or “nisq”or “nmr quantum comput*”or “noisy intermediate scale quantum”or “one-way quantum comput*”or “optical comput*”or “qaoa”or “quantum advantage”or “quantum algorithm*”or “quantum annealing”or “quantum approximate optimization algorithm*”or “quantum automata”or “quantum cellular automata”or “quantum circuit*”or “quantum compilation”or “quantum compiler*”or “quantum complexity”or “quantum complexity theory”or “quantum comput*”or “quantum computation and information”or “quantum computation architectures and implementation*”or “quantum computational complexity”or “quantum computational logic*”or “quantum computer simulation*”or “quantum computing simulation*”or “quantum cost*”or “quantum counting algorithm*”or “quantum decryption”or “quantum error correction”or “quantum evolutionary algorithm*”or “quantum finite automata”or “quantum fourier transform*”or “quantum game*”or “quantum gate*”or “quantum genetic algorithm*”or “quantum image proces*”or “quantum information proces*”or “quantum knot*”or “quantum lattice gas automata”or “quantum logic gate*”or “quantum logic synthesis”or “quantum logic*”or “quantum machine learning”or “quantum neural network*”or “quantum neuron*”or “quantum optimization”or “quantum parallelism”or “quantum phase estimation algorithm*”or “quantum private comparison”or “quantum programming”or “quantum programming languages”or “quantum query algorithm*”or “quantum query complexity”or “quantum recommendation”or “quantum register*”or “quantum search algorithm*”or “quantum search*”or “quantum simulation*”or “quantum software”or “quantum speedup”or “quantum supremacy”or “quantum turing machine*”or “quantum verification”or “quantum volume*”or “quantum walk*”or “shor's algorithm”or “superconducting quantum comput*”or “superconducting qubit*”or “surface code”or “topological quantum comput*”or “topological qubit*”or “universal quantum comput*”or “variational quantum eigensolver”or “variational quantum unsampling”or “vqe”

Technology	Search Terms
Communications	“bell inequalities”or “bell inequality”or “bell state*”or “bell state measurement”or “bell states”or “controlled quantum communication*”or “entanglement concentration*”or “entanglement distillation*”or “entanglement distribution”or “entanglement swap*”or “epr pair*”or “free-space quantum communication*”or “heralded single photon source*”or “heralded single-photon source*”or “long-distance quantum communication*”or “qber”or “quantum bit commitment”or “quantum bit error rate*”or “quantum channel*”or “quantum communication*”or “quantum communication channel*”or “quantum communication complexity”or “quantum communication network*”or “quantum communications”or “quantum dense coding*”or “quantum dialogue”or “quantum direct communication*”or “quantum discord”or “quantum internet”or “quantum key distribution*”or “quantum network*”or “quantum networks”or “quantum private quer*”or “quantum repeater*”or “quantum repeaters”or “quantum router*”or “quantum sealed-bid auction*”or “quantum shannon theor*”or “quantum state sharing”or “quantum teleportation”or “remote state preparation*”or “superdense coding*”or “the bell state measurement*”or “quantum cryptogr*”or “semi-quantum cryptogr*”or “quantum secret sharing”or “controlled quantum secure direct communication*”or “quantum secure direct communication*”or “deterministic secret quantum communication*”or “deterministic secure quantum communication*”or “quantum signature*”or “quantum blind signature*”or “quantum private comparison*”or “quantum encryp*”or “quantum authentication”or “quantum identity authentication*”or “secure quantum communication*”or “arbitrated quantum signature*”or “quantum secure communication*”or “qsdc”or “quantum communication security”or “y-00 protocol*”or “quantum steganogra*”or “continuous variable quantum key distribution*”or “continuous-variable quantum key distribution*”or “quantum key distribution*”or “measurement-device-independent quantum key distribution*”or “qkd”or “qkd network*”or “b92”or “b92 protocol*”or “bb84”or “bb84 protocol*”or “decoy state*”or “quantum key agreement”or “measurement device independent”or “measurement-device-independent”or “semi-quantum key distribution*”or “decoy state protocol*”or “decoy states*”or “quantum one-time pad*”or “quantum key distribution network*”or “quantum key distribution protocol*”or “photon number splitting attack*”
Sensing	“quantum sensing”or “quantum sensor*”or “quantum metrology”or “atom interferometry”or “n00n state*”or “atomic sensor*”or “quantum gyroscope*”or “quantum accelerometer*”or “quantum ins”or “quantum imu”or “quantum magnetometer*”or “quantum rf receiver*”or “cold-atom interferometer*”or “cold-atom gas interferometer*”or “heisenberg limit*”or “standard quantum limit*”or “quantum inertial sens*”or “quantum gravimeter*”or “quantum electrometer*”or “quantum radio*”or “quantum receiver*”or “rydberg atom sensor*”or “vapor-cell sensor*”or “defect-based sensor*”or “scanning quantum dot microsco*”or “qubit detector*”or “quantum detector*”or “quantum detector tomography”or “quantum tomography”or “quantum state tomography”or “microwave bolometer*”or “microwave bolometer*”or “quantum illumination”or “ghost imaging”or “quantum dot imaging”or “quantum imaging”or “quantum radar*”

Source: Parker *et al.* (2022)

Appendix D Patent Classification Criteria and Supplemental Data

Patent topics were sorted by concept as described by Aboy *et al.* (2022). In Table D.1, "TAC" refers to patents with keywords appearing in title, abstract, or content. Search codes (e.g., CPC:H01L) are described as:

> *USPTO & EPO patent application and grant data from 20010101 to 20211231 (search conducted by MA on 20220218). CPC class G06N10/00 is devoted to "Quantum computing, i.e. information processing based on quantum-mechanical phenomena"; B82Y20/00 to "Nanooptics, e.g. quantum optics"; B82Y10/00 to "Nanotechnology for information processing, storage or transmission, e.g. quantum computing or single electron logic"; H04L9/0852 to "Quantum cryptography (transmission systems employing electromagnetic waves other than radio wave"); H04B10 to "Transmission systems employing electromagnetic waves other than radio waves, e.g. infrared, visible or ultraviolet light, or employing corpuscular radiation, e.g. quantum communication"; H01L to "Semiconductor Device; Electric Solid State Devices."*

Table D.1 Quantum Technologies Patented in the U.S. (USPTO) and Europe (EPO) by Search Term, 2001–2021

ID	Search Concept	Search Term	Applications	Granted
S1	Quantum-related patents	"quantum" (and related keywords)	236,642	178,033
S2	Quantum patents (TAC)	S1 & TAC: quantum	34,402	20,581
S3	Quantum claims	ACLM: quantum	30,385	18,696
S4	Quantum-independent claims	ICLM: quantum	14,672	10,318
S5	Quantum devices	S2 & CPC:H01L	14,243	8,965
S6	Nanostructures/ quantum optics	S2 & CPC:B82Y20/00	4,917	3,282
S7	Quantum information processing	S2 & CPC:B82Y10/00	3,331	2,057
S8	Quantum computing	S2 & CPC:G06N10/00	3,042	1,603
S9	Quantum cryptography	S2 & CPC:H04L9/ 0852,55,58	1,219	736
S10	Quantum communications	S2 & CPC:H04B10	1,057	632

Data Source: Aboy *et al.* (2022)

Table D.2 Most Active USPTO and EPO Patent Assignees, 2001–2021, Ranked by Patents Obtained

Assignee	Patents	Assignee	Patents
IBM	254	COMMISSARIAT ATOMIQUE	9
D WAVE SYSTEMS	**183**	RAYTHEON TECH CORP	9
NORTHROP GRUMMAN	120	SEEQC INC	9
MICROSOFT CORP	111	STMICROELECTRONICS	9
ALPHABET INC	59	HARVARD COLLEGE	8
RIGETTI & CO INC	53	MAGIQ TECH INC	8
TOSHIBA CORP	37	CALIFORNIA INST OF TECH	7
INTEL CORP	32	HP INC	7
HONEYWELL INT INC	26	NEC CORP	7
U.S. GOVERNMENT	26	STANFORD UNIV	7
HP ENTERPRISE	23	UNIV SYS OF MARYLAND	7
NEWSOUTH INNOVATIONS	22	UNIV WISCONSIN WARF	7
MASS INST OF TECH	20	KYNDRYL INC	6
EQUAL1LABS INC	16	MITRE CORP	6
HITACHI LTD	15	PARALLEL INVESTMENT	6
JAPAN SCIENCE & TECH AG	15	QC WARE CORP	6
QUANTUM MACHINES	15	SEOUL SILIP UNIV	6
1QB INFORMATION TECH	**14**	TECHNISCHE UNIV DELFT	6
ACCENTURE PUBLIC LTD	12	UNIV JOHNS HOPKINS	6
IONQ INC	12	UNIVERSAL RES KK	6
NOKIA CORP	12	WELLS FARGO BANK	6
BANK OF AMERICA	11	CORNING CORP	5
ELEMENT SIX SA	11	DARTMOUTH COLLEGE	5
GOV. OF ABU DHABI	11	LOCKHEED MARTIN CORP	5
UNIV OXFORD	11	PHOENIX CO OF CHICAGO	5
YALE UNIV	10	**QUANTUM VALLEY INVEST**	**5**

Data Source: Aboy *et al.* (2022)

Canadian organizations are displayed in bold.

Appendix E Technology Transfer Metrics for Select Canadian and U.S. Universities

Table E.1 Technology Transfer Metrics for Select Canadian (2020) and U.S. (2022) Universities/Colleges with Quantum Technology Programs, Normalized by Research Expenditures

Institution	Licensing Full-Time Equivalents	Total Licences	Total Options	Gross Licence Income	Disclosures	New Patent Applications	Start-ups	Active Licences and Options	Issued Patents
	per CA$100M								
CANADA									
University of Calgary	1.27	5.59	0.25	0.21	33.06	4.32	4.58	38.65	2.54
University of British Columbia	1.19	9.62	3.43	5.65	21.60	10.54	1.84	77.86	3.03
McMaster University (incl. Hamilton Health Science & St. Joseph's Healthcare Hamilton)	3.32	40.07	0.69	1.48	30.40	15.89	3.11	59.41	5.18
University of Toronto (excl. affiliated hospitals)	1.48	5.61	0.99	9.99	20.12	13.19	2.31	54.75	7.26
University of Waterloo	2.65	1.63	0.00	0.04	8.97	8.97	5.71	53.84	3.26
McGill University	1.39	3.19	2.59	0.31	25.70	12.95	2.79	40.24	3.19
Université de Sherbrooke (TransferTech Sherbrooke)	1.32	2.20	2.64	1.89	12.75	19.79	1.32	40.90	2.20
University of Victoria	2.57	2.57	0.00	0.31	35.07	10.27	2.57	26.52	4.28
Queen's University	0.53	3.74	1.07	0.42	22.95	4.80	0.53	29.89	7.47

Institution	Licensing Full-Time Equivalents	Total Licences	Total Options	Gross Licence Income	Disclosures	New Patent Applications	Start-ups	Active Licences and Options	Issued Patents
per CA$100M									
UNITED STATES									
MIT Lincoln Laboratory	1.74	6.88	2.40	5.83	49.01	25.91	1.60	94.62	29.18
University of California Berkeley (California System)	1.50	4.78	1.12	2.26	27.22	15.13	1.34	0.00	2.34
University of Illinois at Urbana-Champaign	1.57	8.75	2.81	4.93	38.33	16.20	0.86	72.02	11.12
University of Maryland Joint Quantum Institute (Maryland System)	1.15	6.14	2.74	0.32	34.32	21.93	2.41	58.11	14.69
University of Southern California Center for Quantum Information Science and Technology (CQIST)	1.57	6.95	0.79	0.78	32.67	12.73	1.44	48.94	9.05
California Institute of Technology	2.51	10.55	3.77	1.61	47.24	46.99	2.01	121.11	41.96
Stanford University	1.89	9.28	3.09	8.89	35.83	29.49	1.73	98.89	16.90
Harvard University	1.51	13.18	7.42	14.56	52.60	24.72	3.71	161.91	26.50
Carnegie Mellon University	3.03	15.34	0.70	4.93	120.96	102.13	1.39	215.07	18.13

Data Source: AUTM (2022a, 2022b)

Based on the Bank of Canada's 2021 annual exchange rate (US$1 = CA$1.2535) (Bank of Canada, n.d.).

Appendix F Canada's Quantum Ecosystem and National Quantum Strategy

Table F.1 Canada's National Quantum Strategy Funding and Programming and Other Programming

Provider	Programming	Amount ($ millions)	Duration	Details
Research				
NQS				
NSERC	Alliance Grants (all)	132.5	7 years	
	Quantum	62.4		University researchers collaborating with private, public, and not-for-profit partners. Grants range from $50,000-$300,000 over 1-5 years.
	International Quantum	29.7		University researchers growing international research collaborations. Grants up to $25,000 for one year.
	Consortia Quantum	40.4		Large-scale domestic research collaborations across regional hubs. Grants range from $500,000-$1 million per year for 3-5 years.
NRC	Quantum Research and Development Initiative	9.0	6 years	Develop partnerships among government, academia, and industry to support NQS priorities.
Other Programming				
Tri-agency	Canada 150 Research Chairs (C150)			
	Canada Excellence Research Chairs (CERC)			
	Canada First Research Excellence Fund (CFREF)			
	New Frontiers in Research Fund (NFRF)			

Provider	Programming	Amount ($ millions)	Duration	Details
NSERC	Discovery Grants			Ongoing programs with long-term goals.
	NSERC-NSF collaboration on quantum sciences and AI			MOU on research co-operation.
CFI	Innovation Fund			Invest in infrastructure across areas of research.
	John R. Evans Leaders Fund			Attract and retain talent.
Federal Departments	Canadian International Innovation Program (CIIP)			Global Affairs Canada to support Canadian companies in pursuing international R&D collaborations with commercialization potential.
	Innovation for Defence Excellence and Security (IDEaS)			Department of National Defence and Defence Research and Development Canada call for proposals, emphasizing sensors.
Third-Party	Perimeter Institute for Theoretical Physics			
Talent				
NQS				
NSERC	CREATE	5.4	6 years	Support the training of teams of HQP (students and post-doctoral fellows). Grants range in value and duration: up to $150,000 in the first year, expanding to as much as $300,000 for the next 5 years, up to a maximum of $1.65M over 6 years.
Mitacs		40.0	6 years	Support for attracting, training, retaining, and deploying highly qualified personnel through internships and professional skills development.

Provider	Programming	Amount ($ millions)	Duration	Details
Other Programming				
Immigration, Refugees and Citizenship Canada	Canadian Experience Class			Current and former temporary foreign workers and international students in high-skill occupations and official language proficiency.
	Federal Skilled Trades Program			Foreign workers in certain high-skilled trades may be eligible for permanent residence.
	Federal Skilled Workers Program			Certain highly skilled workers with high human capital.
	Global Skills Strategy			Faster application processing times and work permit exemptions to help employers find highly skilled workers quickly.
	Provincial Nominee Program			Allows provinces and territories to address their specific economic development needs.
Other Federal Programming	Global Talent Stream			Employment and Social Development Canada relies on the Temporary Foreign Worker Program to fill in-demand, highly skilled positions on the Global Talent Occupations List.
	Post-doctoral Fellowship/ Research Programs			NRC and others; early-career scientists are given access to world-class facilities and opportunities to work with research teams in Canada (2-year terms are common).
	Research Affiliate Program			Public Service Commission of Canada — full- or part-time positions for students to work as research affiliates with the Government of Canada.
Commercialization				
NQS				
ISED	Global Innovation Clusters	14.0	7 years	Supports development of high-density areas of companies, academic institutions, and not-for-profit organizations.
	Innovative Solutions Canada	35.0	7 years	Facilitates matching Government of Canada clients with Canadian SMEs in early-stage research or late-stage testing.

Provider	Programming	Amount ($ millions)	Duration	Details
NRC	Challenges Program	50	7 years	Support two challenge programs - the Quantum Sensors Challenge, and the Applied Quantum Computing Challenge.
Regional Development Agency Support	Canada Economic Development for Quebec Regions	23.3	7 years	Funding and support for SMEs and not-for-profit organizations throughout Quebec.
	Federal Economic Development Agency for Southern Ontario	23.3	7 years	Funding and support for SMEs and not-for-profit organizations throughout Southern Ontario.
	Prairies Economic Development Canada	9.4	7 years	Funding and support for SMEs and not-for-profit organizations throughout Alberta, Saskatchewan, and Manitoba.
	Pacific Economic Development Canada	14	7 years	Funding and support for SMEs and not-for-profit organizations throughout British Columbia.
Other Programming				
Federal Departments and Agencies	Canada Trade Commissioner Service			Global Affairs Canada — international business development and networking.
	High-Throughput and Secure Networks Challenge Program			NRC — collaborative R&D projects on quantum communications.
	IRAP			NRC — advice, connections, and funding for SMEs to increase innovation capacity.
	Space Technology Development Program			Canadian Space Agency — space technologies and innovation for the Canadian space industry.
	Quantum Encryption and Science Satellite (QEYSSat)			Canadian Space Agency — demonstrate quantum key distribution technology.
	Strategic Innovation Fund			ISED – large-scale, transformative, and collaborative projects targeting industry.
	Deep Tech Venture Fund			BDC — companies working in deep tech, including quantum.

Source: ISED (2023d)

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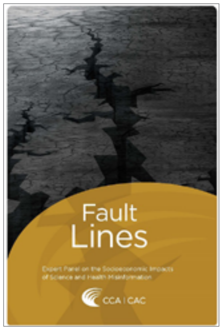
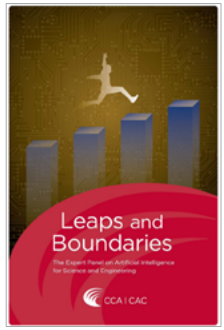
CCA Reports of Interest

The assessment reports listed below are accessible through the CCA's website (www.cca-reports.ca):

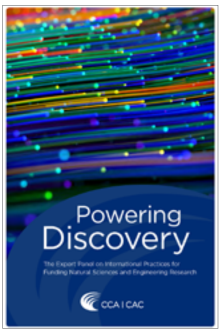
Vulnerable Connections (2023)



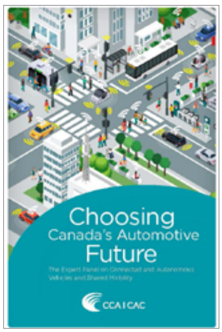
Fault Lines (2023)



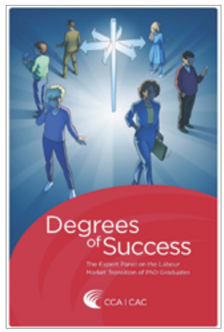
Leaps and Boundaries (2022)



Powering Discovery (2021)



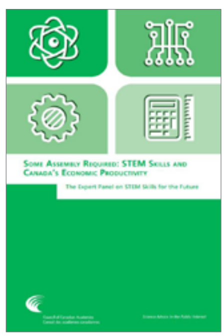
Choosing Canada's Automotive Future (2021)



Degrees of Success (2021)

Improving Innovation Through Better Management (2018)

Competing in a Global Innovation Economy: The Current State of R&D in Canada (2018)



Some Assembly Required: STEM Skills and Canada's Economic Productivity (2015)

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