



National  
**Quantum Strategy**

**National Quantum Strategy Roadmap**  
**QUANTUM COMPUTING**



Government  
of Canada

Gouvernement  
du Canada

**Canada**

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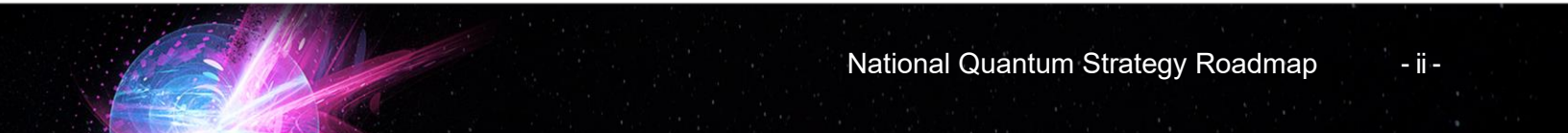
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# Introduction

Advances in quantum science have the potential to transform how people work and live. Investments over many decades have made Canada a global leader in quantum technologies and research, with a growing ecosystem of world-class centres of quantum expertise in universities and businesses across the country. As the rest of the world expands their own quantum strategies and initiatives, Canada must continue to invest wisely, innovate, and commercialize to stay ahead while ensuring it is positioned as an integral contributor to the global supply chain.

To strengthen Canada's quantum ecosystem, the Government of Canada launched the [National Quantum Strategy \(NQS\)](#) in January 2023, and allocated \$360 million in dedicated funding, in addition to leveraging a number of broad-based, large-scale programs. The NQS aims to: amplify Canada's strength in quantum research; grow quantum technologies, companies and talent; and solidify Canada's global leadership in quantum science and its commercialization. The NQS sets out three key missions on: quantum computing and software; communication and post-quantum cryptography; and sensors. To pursue these missions, NQS activities are supporting the three pillars of research, talent and commercialization. Success requires collective effort by many actors, including governments (federal, provincial, territorial and Indigenous governments and organizations), academia and industry, as well as non-profits such as incubators, accelerators and industry associations.



Road-mapping exercises engaged stakeholders to help identify challenges, gaps, opportunities, milestones and actions required to achieve success in each of the NQS missions. Provinces actively involved in the development of quantum hubs were engaged and their input has been incorporated. However, other provinces and territories may also be undertaking actions to support quantum science and technology. Informed by these roadmaps, the Government is working with partners to advance the missions and may explore additional investments.

**This roadmap charts a course forward for the quantum computing hardware, software, algorithms and applications mission.** It will be updated periodically to reflect advances in quantum technologies that could drastically change timelines or lead to new applications.

# Overview of quantum computing hardware and software

Quantum computers (hardware) harness the principles of quantum mechanics such as superposition, interference and entanglement to perform calculations. While classical computers store and process information in binary bits (i.e., 0 or 1), quantum computers do this by exploiting the superposition principle and use quantum bits (or qubits), where 0 and 1 are encoded simultaneously into quantum systems, such as atoms, spins and superconducting systems. This property can allow quantum computers to solve complex problems beyond the ability of classical computers, with potential applications in machine learning; advanced materials, process, molecule and drug simulations; as well as optimization and logistics.

At present, there are many quantum computing platforms including superconducting, photonic, silicon spin, neutral atoms or ion trap-based technologies<sup>1</sup>. There are also different quantum computing systems such as quantum annealers and gate-based systems<sup>2</sup>. Quantum software and algorithms enable the operation and design of quantum computers, and the development of applications. These quantum hardware systems often interact with classical computers, with growing opportunities for quantum-classical hybrid applications.

Forecasts anticipate that quantum computing hardware and software will account for up to US\$68 billion globally by 2030<sup>3</sup>. Canada is well-placed to be a key player due to trusted world-class expertise across the country, comprising a growing ecosystem of universities, industry pioneers along with start-ups, service providers and larger domestic and multi-national firms including regional quantum hubs in Alberta, British Columbia, Ontario and Quebec.

Canadian researchers and companies are at the forefront of the international race to build a scalable, high-performance, fault tolerant quantum computer. Canadian firms have developed quantum computing systems and algorithms with the potential for solving challenges that are too complex, costly or time-consuming to solve with conventional technologies.

Developing a strong Canadian quantum software and service industry is critical as well. Canadians are also leaders in developing software to control quantum computers and link them to classical computer systems, and creating applications that make these systems useful. This advantage could benefit Canadians by transforming a number of sectors, such as making supply chains more efficient, modelling climate change, developing new materials and drugs, and more. Early-stage quantum applications are already being implemented, supporting industry awareness and demonstrating potential applications that will drive industrial progress and further promote the quantum sector.

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<sup>1</sup> For more information on the different quantum computing platforms, please see [Annex A](#).

<sup>2</sup> Quantum annealing uses continuous time quantum fluctuations to find the minimum (optimal) solution among a large set of possibilities, and specializes in optimization problems. Quantum gate-model computing uses sequences of quantum logic gates to perform complex computations on a broader range of problems.

<sup>3</sup> Quantum Canada: Socio-Economic Impact Assessment: 2023 Update, Doyletech, 2023.

# Quantum computing hardware and software mission

**Make Canada a world leader in the continued development, deployment and use of quantum computing hardware and software—to the benefit of Canadian industry, governments and citizens.**

**This mission's long-term goal is to build and scale a fault tolerant quantum computer.** Although quantum computers are currently available, their error rates are high and qubit counts are low, making their utility limited to solving specific, pre-defined problems. Several research and development challenges need to be addressed to achieve this goal.

Support in the near term will focus on research needed to develop and test the next breakthroughs in hardware and other elements of the full computing stack; transitioning R&D into commercial settings through developing use cases and applications; as well as growing the quantum workforce. To support the quantum computing hardware and software mission, the following priorities have been identified:

## **Developing components of a quantum computer and securing the supply chain**

- Develop quantum computing hardware, including hybrid parallel processing systems, simulation and modelling of quantum hardware
- Develop new quantum algorithms and advance quantum computing software
- Identify and alleviate supply chain and infrastructure challenges and develop domestic manufacturing capacity
- Provide access to multiple quantum computing platforms including annealing and gate-model quantum computing systems and various qubit modalities

## **Increasing adoption of quantum computing technologies by receptor sectors**

- Develop proofs of values and use cases, linking producers with end users to support adoption
- Consider ways of offsetting research and development and integration costs and accelerate testing and development of commercial applications
- Develop quantum resource estimations, benchmarks and standards

## **Supporting the quantum computing ecosystem**

- Strengthen the talent pipeline
- Promote Canadian quantum computing science, technology and industry domestically and internationally
- Address barriers to growth for Canadian quantum computing and software companies
- Identify societal impacts and develop an ethics framework
- Protect intellectual property (IP) and improve the security posture of Canadian researchers and innovators

# Programming supporting the quantum computing mission

There are several programs and initiatives across the Government of Canada that are already supporting the quantum computing mission:

- in 2022, Innovative Solutions Canada (ISC) launched a call to develop a [dilution refrigerator](#) in support of quantum computing technologies and a call to test pre-commercial [quantum computing](#) prototypes
- the National Research Council has launched an [Applied Quantum Computing Challenge program](#) to build on Canada's position as a global leader in applied quantum computing
- the Natural Sciences and Engineering Research Council of Canada (NSERC) [announced \\$51 million in awards to 75 recipients in quantum science and technology](#) through the Alliance and Collaborative Research and Training Experience (CREATE) programs in April 2023
- the Bank of Canada is collaborating with Canadian and international quantum researchers, the public sector, and industry through the [Partnerships in Innovation and Technology \(PIVOT\) program](#)

Furthermore, the Department of National Defence and Canadian Armed Forces released its Quantum Science and Technology Strategy Implementation Plan, [Quantum 2030](#), in 2023. It identifies four promising quantum technologies with defence and security applications and lays out a seven-year plan to develop prototypes, including in quantum computing (quantum algorithms for defense and security) ready to be tested in the field by 2030.

Fundamental research that aims to advance our understanding of the science underlying future breakthroughs is important for success and is supported through existing mechanisms such as [NSERC Discovery Grants](#).

Applied research that aligns with the three NQS missions is funded through specific calls under [NSERC Alliance](#) and ISC. Business and non-profit support will continue to be provided through the [Industrial Research Assistance Program \(IRAP\)](#), [Strategic Innovation Fund](#), Regional Development Agency programming, [Global Innovation Clusters](#), [Strategic Science Fund](#), [Innovation for Defence Excellence and Security](#), [Deep Tech Venture Fund](#), etc.

**CIFAR** supports academic research, training, and knowledge mobilization, through its [Quantum Information Science](#) and [Quantum Materials](#) programs, and [CIFAR Azrieli Global Scholars](#) program. CIFAR-supported researchers have contributed to fundamental research and technological advances in a range of topics, from superconductivity and graphene-based two-dimensional materials, to distributed quantum networks and quantum error correction. There have been 19 Global Scholars affiliated with CIFAR's two quantum research programs since 2016.

# 1. Developing components of a quantum computer and securing the supply chain

There are many quantum computing platforms under development, each advancing at a different speed and technology readiness level. [Annex A](#) includes a summary of platforms and their advantages and disadvantages. Given the current level of development, it is not yet clear which platforms will produce a fault tolerant quantum computer. As such, Government programs will be inclusive of different hardware and software approaches.

While impressive progress has been made in the development of quantum computing modalities, advances are still needed to achieve fault tolerant quantum computing. Gate model quantum hardware and software development must advance further to become capable of solving problems that are useful to end users. Research is needed to identify the threshold for when classical approaches to optimization becomes intractable and to what extent quantum gate and annealing systems will deliver broad commercial advantage.

- **Qubit performance:** Several aspects of qubit performance will need to advance to enable the scale up of quantum computing including:
  - develop a scalable qubit and control architecture that includes error correction
  - demonstrate logical qubit performance in a scalable architecture
  - demonstrate interacting logical qubits
  - develop general purpose quantum processing units (QPU) capable of running a well-defined target application
- **Quantum processor modelling:** Modelling the performance of quantum processors, including noise, heat dissipation and other challenges can improve the design of processors, error correction codes and scaled-up systems, and predict processing capabilities. Before fault tolerant quantum computers are available, modelling will help us understand the types of problems that can be best addressed by these systems and test how different hardware approaches would perform without investing in prototype systems. In addition, device simulation software may help training the workforce at institutions where access to quantum computing hardware is limited.
- **Quantum simulation:** Outside of gate-based quantum computing, there is vast potential for simulating problems using quantum systems. Initiatives that could help support adoption include developing programmable quantum simulators for computationally intensive problems beyond the reach of classical computers.
- **Hybrid computing capacity:** Exploiting the full benefits of quantum computing will require interconnected systems of quantum and classical computers, to make use of what each type of system does best and to make it easy for users to access quantum computers in a trusted and private way. This parallel processing will require research and development of novel algorithms or techniques to pass information between the classical and quantum processors, or interconnects and hardware.
- **Distributed quantum computing:** With limited processor sizes, the ability to distribute entanglement between processors and perform “multicore” operations across a network would expand the effective size of the processor. This requires the development of quantum computers that can interface with networking channels. Distributed quantum computing and blind quantum

computing, which would allow for use of quantum computers on untrusted sites, are further explored in the quantum communications roadmap.

## Key challenges

Quantum computing is a complex area of active research that requires advances in multiple open problems to become successful. This section outlines some of the key challenges, although given the emerging nature of the field, it is not possible to provide a complete list.

### Access to foundries and other manufacturing limitations

There is limited domestic industry supporting the quantum computing supply chain, e.g., superconducting chip fabrication, dilution refrigeration manufacturers for at-scale systems and domestic integration of high performance computing and quantum data centres that are inclusive of different computing technologies.

Several approaches to quantum computing (superconducting, photonics, spins, quantum dots, etc.) rely upon modifications to the existing technology used for manufacturing silicon-based integrated circuits. To scale up beyond university lab experiments, access to commercial grade foundries is required.

One barrier is the lack of Canadian semiconductor manufacturing firms and infrastructure. Smaller companies and researchers rely on foundry services to complete their prototypes with processes that can be scaled up to mass manufacturing. In Canada, there are few facilities that can fabricate quantum components at scale. Currently, commercial prototype designs must be sent out of Canada to be fabricated and some Government programs are restricted from funding these activities. Furthermore, a robust process to reliably produce quantum chips at scalable levels, similar to mature technologies like CMOS, is not yet available.

Capturing more of the supply chain for development activities inside Canada can increase supply chain resiliency and security, generate economic growth, and foster innovation and collaboration. Discussions between the government and the quantum community can help determine the necessity and feasibility of a domestic footprint for quantum computer components. In cases where key components are only available internationally, establishing agreements to secure Canadian access may be necessary. Enhancing our understanding of the global supply chain and determining Canada's role within it will be necessary.

### Software and algorithms

The development of quantum software faces additional hurdles, such as super-polynomial speed-up for simulating error correction codes. Quantum computer codes should have encoding and decoding efficiencies to enable quantum error correction and distributed quantum computing, reduce overhead, and avoid lag in the communication between quantum and classical devices.

Algorithms that make use of noisy quantum computers are in high demand, because they can lower the physical and engineering requirements for building useful quantum machines. Recent demonstrations of high fidelity computations on present day hardware with over one hundred physical qubits suggest that useful quantum computing applications are possible in the near-term with error mitigation schemes instead of requiring full error correction.<sup>i,ii,iii,iv</sup> Such algorithms can provide applications and benchmarks for current quantum computers, and insight into the potential of quantum computing systems, which can incentivize larger scale adoption. Development of algorithms and software for use cases on near-term

systems will ensure that businesses and researchers are ready to quickly realize the full advantages of fault-tolerant hardware once it is available. The development of quantum simulators capable of optimizing the generation, fusion, and measurement protocols in noisy environments is also required.

Given that the commercialization of annealing and gate-based systems is anticipated to speed up as hybrid quantum-classical algorithms expand, research and development of innovative hybridization techniques is also required. Ultimately, advancing quantum software is critical in developing applications that drive adoption, thus increasing demand for hardware and the rest of the quantum computing supply chain.

#### Establishing a cost-effective supply chain for critical materials and components

Developing a quantum computer may require materials or components that may either be unavailable or prohibitively expensive. In many cases, these materials and components are not currently produced in Canada or not at sufficient levels to meet demand.

Cooling some types of quantum hardware requires helium-3, an isotope that has an unmatched level of efficiency in carrying away the heat. However, helium-3 is extremely rare and the main supply comes from aging nuclear warheads and heavy water reactors. In less than two decades, the global demand for and price of helium-3 has substantially increased. Furthermore, the distribution of helium-3 is highly regulated and is subject to strict government controls due to security concerns.

Similarly, the high-purity (chemical and isotopic) silicon wafers needed for some architectures are becoming increasingly restricted and expensive. Neon gas is a critical component in semiconductor production that is also becoming inaccessible.<sup>v</sup> Expanding access to alternative sources of purified silicon and neon gas is critical to scaling these technologies.

#### Simulation of qubit noise and quantum error correction to help scale architectures

Today's gate-model hundred-qubit quantum computers require a dramatic scale up to potentially millions of qubits to solve certain problems. Although a variety of qubit technologies have been demonstrated, scalability remains a major hurdle. Modelling the noise sources and thermal budget limits of qubits through analytic approaches and technology computer-aided design software will enable the limitations to be better understood and help advance manufacturing capabilities including scale up of quantum computers. Developing and commercializing hardware modeling and design solutions would also enable Canadian companies to become a critical part of the global quantum-hardware supply chain.

Additionally, it will be important to lower error rates so that adding qubits and longer coherence requirements does not undermine system performance or require substantial resources for error correction.

Quantum error correction schemes will also need to be refined in parallel with hardware development to scale quantum computing systems. Quantum error mitigation and suppression methods, which generally use a combination of classical and quantum computations, have demonstrated benefits that could allow quantum computational advantage before full error corrections schemes are usable. While these methods have been implemented in commercial systems, further improvements are needed. Error correction and suppression strategies will also need to be tailored to different qubit platforms.

Quantum annealing systems will need to continue to scale the number of devices and also produce architectures with increased connectivity and enhancements in device coherence.

## Packaging

Widespread adoption of quantum computers will require addressing all parts of the systems, especially the packaging challenge of larger and more complex Quantum Processing Units (QPUs), ensuring that quantum systems or sub-systems can be purchased and used reliably. Developing systems that are standardised, interoperable and robust will help transition the technology from complex lab setups to modular and robust devices. This could involve miniaturisation and streamlining control electronics, automation and environmental shielding.

## Action plan

The objectives in the long term (7+ years) are to:

- develop a 1,000,000+ physical qubits quantum computer
- achieve quantum error correction of 100-1,000 qubits to one logical qubit
- develop a quantum computer (gate-model and annealing) with 100 logical qubits
- develop 100-way inter qubit connectivity
- establish a fabrication ecosystem built around the anchor companies producing key quantum computing components in Canada

The action plans below indicate short (0-3 years) and medium term (3-7 years) actions to develop components of a quantum computer and secure the supply chain.

### **Develop quantum computing hardware, including hybrid parallel processing systems, simulation and modelling of quantum hardware**

Action item	Timeline	Lead
A1. Support and undertake basic and mission-driven applied research to develop quantum computing hardware and tools such as: <ul style="list-style-type: none"><li>• device modelling</li><li>• simulators</li><li>• improved qubit design</li><li>• interfaces</li><li>• control protocols</li></ul> to improve optimization and performance of available systems	Short and medium term	Government of Canada, Academia, Industry/Non-Profit
A2. Support the scaling up of relevant technologies	Short and medium term	Government of Canada, Academia, Industry/Non-Profit
A3. Support and undertake the testing of quantum computational, cost and/or energy advantage	Medium term	Government of Canada, Industry/Non-Profit
A4. Develop first generation gate-model computer (16-100 logical qubits)	Medium term	Industry/Non-Profit
A5. Develop technology infrastructure for quantum device design, fabrication and packaging across a variety of platforms and systems	Short and medium term	Industry/Non-Profit

A6. Support the scaling of quantum computing integrated circuit technology beyond VLSI scale	Short and medium term	Industry/Non-Profit
A7. Facilitate dialogue between academia and industry to establish partnerships on fundamental and applied quantum computing research	Short and medium term	Academia, Industry/Non-Profit

### Develop new quantum algorithms and advance quantum computing software

Action item	Timeline	Lead
A8. Develop algorithms: <ul style="list-style-type: none"> <li>with use cases and advantage that can be realized on current/near-term hardware prior to the development of fault-tolerant quantum computers</li> <li>with provable super-polynomial advantage on fault-tolerant quantum computers</li> <li>hybrid algorithms integrating increasing scale of quantum computing systems and classical computational resources</li> </ul>	Short and medium term	Academia, Industry/Non-Profit
A9. Develop improved methodologies for error correction	Short and medium term	Academia, Industry/Non-Profit

### Identify and alleviate supply chain and infrastructure challenges and develop domestic manufacturing capacity

Action item	Timeline	Lead
A10a. Match most pressing Canadian industry needs to existing infrastructure, and scope out further potential investments (e.g., foundry, computing centre and hybrid infrastructure), in tandem with related sectors such as semiconductors	Short term	Government of Canada, Industry/Non-Profit
A10b. Assess establishing, with mix of public/private funding, national infrastructure for production of quantum components	Medium term	Government of Canada, Industry/Non-Profit
A11a. Create a dialogue to ensure a robust supply chain for critical components and identify how Canada should be integrated into the global supply chain	Short term	Government of Canada
A11b. Protect quantum system supply chain and establish access to internationally-produced materials and technologies with international agreements or other mechanisms	Short and medium term	Government of Canada

### Provide access to multiple quantum computing platforms

Action item	Timeline	Lead
A12a. Assess options to support user access initiatives for commercial quantum computers to support industry and academic R&D and adoption	Short term	Government of Canada
A12b. Assess implementing initiatives to support access to commercial quantum computers for academia and industry	Medium term	Government of Canada

## Provincial actions (as submitted)

Action item	Timeline	Lead
A13. Collaborate with other provinces and industry to gain access to quantum computers to support research in quantum software and application development	Short and medium term	Government of Alberta
A14. Develop quantum software applications to address productivity challenges in core sectors like agriculture, life sciences, and energy	Short and medium term	Government of Alberta
A15. Build on Alberta's expertise in artificial intelligence by enhancing collaboration with Alberta's quantum programming expertise, as well as other quantum computing hubs across Canada to develop solutions for Alberta's core industries	Short and medium term	Government of Alberta
A16. Drive the development of transdisciplinary solutions that address global challenges through the application of quantum technologies and accelerate industry-academic collaboration in quantum computing	Short and medium term	Government of Alberta
A17. Create a quantum testbed to enable B.C. companies working on computing, networking, and the delivery of quantum computing products and services to test end-chain implementation and demonstrate real-world use of quantum computing and networking solutions	Short and medium term	Government of British Columbia
A18. Work with manufacturing companies in B.C. and across Canada to identify parts of the manufacturing value chain that B.C. could support to streamline access, and link to commercialization opportunities	Short and medium term	Government of British Columbia
A19. Establish partnerships with companies that specialize in hardware development to facilitate the growth and advancement of quantum companies involved in algorithm applications for the agriculture, energy, life sciences and financial sector	Short and medium term	Government of Ontario
A20. Build on the success of the Critical Technologies Initiatives and continue to further support non-for-profits and companies working on components of quantum computing with a focus on algorithms and software development	Short and medium term	Government of Ontario
A21. To further advance research in quantum software and application development, continue multi-level collaboration with other provinces and federal government initiatives to address current challenges	Short and medium term	Government of Ontario
A22. Support university research chairs dedicated to the hardware and software design of quantum computers and reinforce partnerships with industry	Short and medium term	Government of Québec
A23. Support efforts, both academic and industrial, to tackle error corrections at the qubit level	Short and medium term	Government of Québec
A24. Support the DevteQ, an open-access, shared laboratory dedicated to quantum computing hardware development and testing, with a goal to eliminate the barrier for startups to access R&D infrastructures	Short and medium term	Government of Québec

A25. Develop an integrated supply chain that provides the tools and facilities (fab, cryo, microelectronics) to facilitate and accelerate the tech transfer from university research to industry, covering the entire TRL spectrum	Short and medium term	Government of Québec
A26. Establish a dedicated state-of-the-art Qubit fabrication facility at the Centre de Collaboration MiQro Innovation (C2MI) in Bromont, QC, the largest microelectronics R&D center in Canada	Short and medium term	Government of Québec
A27. Share facilities, knowledge, and workforce with other provinces and partners	Short and medium term	Government of Québec

## 2. Increasing adoption of quantum computing technologies by receptor sectors

For widespread adoption to occur, end users will need evidence that quantum computers can meet their needs in a manner that is superior (i.e., computational, cost and/or energy advantage) to existing classical technologies. The development of use cases and proofs of value will help demonstrate added value and justify adoption, thus increasing demand.

The full range of potential applications to real-world problems remains uncharted. Quantum computers are good tools for solving problems that have special properties or structure. However, identifying these structures requires a complex theoretic effort, using basic research in quantum algorithms and their capabilities as well as a knowledge of the computational challenges faced by industry. To date, there are only a few algorithms with practical utility. Identifying additional use cases for fault-tolerant quantum computers, annealers and quantum hybrid technologies can help drive the invention of the required algorithms.

Training within firms is also crucial for the diffusion of this technology and widespread adoption.

Furthermore, establishing workflows and data processing pipelines is still needed for scientific and business applications. Quantum resource estimation must be undertaken to determine the hardware requirements.

Other impediments to adoption in receptor industries include:

- low awareness of how quantum technologies can affect them, compounded by lack of in-house quantum talent and quantum literacy
- challenges with interoperability with existing systems and high costs to incorporate quantum technologies into business processes
- lack of awareness of the management of innovation required to adopt disruptive technology
- lack of standardization and regulatory uncertainty on quantum technologies
- risk aversion and resistance to change

Initiatives that help de-risk adoption of quantum technologies by end users, support Canadian participation in standards setting activities, bolster the talent pipeline, and raise awareness of quantum applications, can help address these issues.

## Potential use cases

Multiple sources have identified potential use cases across a wide variety of sectors. A few examples follow:

### Manufacturing

- Materials design: improved materials for automotive, aerospace, and microelectronics<sup>vi</sup>
- Battery design: new high-capacity batteries through a better understanding of chemical reactions using quantum simulations<sup>vii</sup>
- Optimizing manufacturing operations: improve processes that can reduce use of forever chemicals, enhance manufacturing and distribution, reduce emissions and cut waste<sup>viii</sup>

### Banking and financial services<sup>ix</sup>

- Fraud detection: data modelling to find patterns on complex transactional data to detect fraud and anomalies<sup>x</sup>
- Risk profiling: speed up long risk-scenario simulations with higher precision while testing more outcomes

### Healthcare and life sciences

- Diagnostic assistance: improve analysis of medical images and complex biomarker data, leading to more accurate diagnoses and treatment planning<sup>xi</sup>
- Drug discovery: efficiently simulate molecules to develop new drugs more quickly<sup>xii,xiii</sup>

### Transportation and logistics

- Improve operations at ports of entry or transportation networks; emergency response and other logistics problems, including in defence<sup>xiv</sup>

### Agriculture

- Enhance crop management by improving the analysis of complex weather data<sup>xv,xvi</sup>, or developing predictive analytics for forecasting pests and crop yield
- Transform the creation and use of fertilizers and pesticides, in particular with more efficient products needed for agricultural production while reducing harmful effects on the environment

### Natural resources, energy, and climate change

- Seismic imaging: aid resource exploration by analyzing seismic imaging data<sup>xvii,xviii</sup>
- Refining processes: development of mineral extraction and refining processes may be accelerated through chemical simulations<sup>xix</sup>
- Grid optimization: improve electrical grid predictability, provide climate and weather modeling, and increase renewable energy use<sup>xx</sup>

## Emergency management and defence

- Emergency response: enhance weather modeling<sup>xxi</sup> for better predictive analytics and optimize earth observation satellites to assist with wildfire management<sup>xxii,xxiii</sup>
- Shift scheduling: solutions for complex scheduling, e.g. emergency responders and medical staff<sup>xxiv</sup>
- Enhance military decision-making, mission-planning, cyber operations, and targeting<sup>xxv</sup>

## Action plan

The objectives in the long-term (7+ years) are to:

- establish quantum resource estimates for all use cases
- develop a suite of applications showing quantum advantage (computational, cost and/or energy) in commercial processes for gate-model and quantum annealing systems
- develop and adopt industry standards
- increase adoption of quantum computing technologies and applications by leading organizations in key sectors and government

The action plans below indicate short (0-3 years) and medium term (3-7 years) actions to increase adoption of quantum computing technologies by receptor sectors.

### Develop proofs of values and use cases, linking producers with end users to support adoption

Action item	Timeline	Lead
B1. Develop proofs of concept, proofs of value, and use cases for government, receptor industries and early adopters, including by matching academic and industry capabilities to determine scope and requirements with end users, and refine value propositions, etc.	Short and medium term	Government, Academia, Industry/Non-Profit
B2. Identify portfolio of applications and problem classes benefiting from current/near-term and large-scale (10,000+ qubits) quantum annealing and gate systems and the best platform for each use case	Short and medium term	Industry/Non-Profit
B3. Assess funding proof-of-concept projects on uses of quantum computing in government departments	Short and medium term	Government of Canada

### Assess ways of offsetting R&D and integration costs and accelerate testing and development of commercial applications

Action item	Timeline	Lead
B4. Assess investing in pilot projects and sandboxes where end-users from industry and Government can test applications	Short and medium term	Government of Canada

### Develop quantum resource estimations, benchmarks, and standards

Action item	Timeline	Lead
B5. Develop quantum resource estimation for use cases	Short and medium term	Academia, Industry/Non-Profit

B6a. Help industrial users better understand capabilities and performance criteria by developing high-level metrics and application-oriented benchmarks	Short term	Industry/Non-Profit
B6b. Further identify platform specific benchmarks, such as computation time, latency, problem size, approximation rate, resolution probability, accuracy, fidelity, etc., for the resolution of several problem classes across multiple domains	Medium term	Industry/Non-Profit
B7a. Support the participation of industry and government organizations in domestic and international standards development activities, and raise awareness of new standards as they are established	Short and medium term	Government, Industry/Non-Profit
B7b. Implement industry standards	Medium term	Government, Industry/Non-Profit

### Provincial actions (as submitted)

Action item	Timeline	Lead
B8. Support Alberta's core industries to promote quantum adoption in Alberta	Short and medium term	Government of Alberta
B9. Build on access to quantum hardware platforms to provide researchers and companies with hands-on experience working with quantum computers. Explore potential collaboration with other quantum hubs.	Short and medium term	Government of British Columbia
B10. Work with B.C.'s quantum companies to develop industry use cases applying quantum computing technologies to real world business challenges	Short and medium term	Government of British Columbia
B11. Work with B.C.'s non-quantum companies to raise awareness of opportunities and impacts from quantum computing and help test proof-of-concept projects to build knowledge and experience of quantum applications to advance industry and protect against post-quantum threats	Short and medium term	Government of British Columbia
B12. Leverage communication pieces by demonstrating cutting-edge research in quantum computing by institutions and recent proof-of-concepts by companies, highlighting innovative solutions for industry sectors	Short and medium term	Government of Ontario
B13. The Ontario government, through the Ontario Research Fund, will provide research institutions with funding operational costs associated with major projects and projects that have strategic value. For instance, the Experimental Research stream funding will support projects demonstrating strong commercialization potential. Applications focused on Ontario's critical technologies, such as quantum computing, will be given priority.	Short and medium term	Government of Ontario
B14. Provide access to a diversity of quantum computing technologies and platforms to be used as test beds for academia and end users in Quebec, Canada and abroad, including a dedicated, data-sovereign IBM Quantum System One located in Bromont, QC.	Short and medium term	Government of Québec

B15. Provide access to a hybrid HPC-Quantum platform	Short and medium term	Government of Québec
B16. Set up and promote educational tools and access to expertise in order to facilitate the adoption of quantum computing technologies in all sectors	Short and medium term	Government of Québec

## 3. Supporting the quantum computing ecosystem

Several initiatives can be undertaken to support the quantum computing ecosystem as a whole. These initiatives will also address issues identified in the other priorities.

### Attraction, development and retention of a quantum workforce

A diverse, skilled and large quantum workforce will be needed to support the activities described in this roadmap. This includes highly qualified personnel with scientific skills to develop advances in fundamental quantum science, technical skills to develop quantum technologies and entrepreneurial skills to bring research from the lab to the market. Quantum-literate employees, entrepreneurs and researchers, along with technicians trained in the installation, integration, operation, repair and maintenance of quantum technologies and associated components such as dilution refrigerators are also needed.

Partnerships and coordination between academia and industry on training will help ensure that future talent needs are met. This could include providing access to quantum technologies for students, identifying industry training needs, jointly developing curriculum and creating co-op/internship opportunities.

It will be critical for Canada to invest in developing and retaining quantum expertise, as well as accessing global pools of talent. Being internationally competitive on student, postdoctoral and industry compensation and the work environment will be key. In addition, there is a need to increase the number of graduates with quantum-related skills. Efforts must also continue in addressing the underrepresentation of equity-seeking groups in scientific, technology, engineering and mathematics disciplines (STEM).

Talent for quantum R&D also comes from a global marketplace and bringing that talent to Canada and retaining them can be challenging. Visa timing and costs can increase the complexity of this process. Canada must make it as easy and quick as possible to bring and keep those with quantum expertise.

In December 2022, the National Quantum Strategy Secretariat held two virtual workshops led by Immigration, Refugee and Citizenship Canada, which provided an overview of immigration programming and a Q&A session. More work will be needed to address this issue.

### Ethical and social considerations

The broad usage of quantum computers may impact many sectors of the economy. It will be necessary to identify social implications and ethical considerations. This could include:

- export of technologies that could have dual uses in the civilian and military sectors
- equity, diversity and inclusion considerations in the quantum workforce and among those who would benefit from the technology
- environmental impact of quantum technologies
- potential of quantum computers to break widely used encryption methods with impacts on privacy and security

In addition, quantum machine learning may result in faster data analysis, processing of larger datasets, and useful generalizations from a smaller amount of training data than is possible with classical machine learning. This could enable improved identification and surveillance, resulting in privacy impacts.

Quantum machine learning and artificial intelligence (AI) may also exacerbate discrimination against marginalized groups when trained on bad data and biased algorithms and used in automated decision-making systems (e.g., hiring, medical diagnosis, etc.).<sup>xxvi</sup>

In view of these observations, learning from ethical issues and regulations in AI and other emerging technology areas, and applying them to quantum technologies is key. This will help mitigate unintended consequences in the development of regulations. Further research on the social impacts of quantum technologies and development of an ethics framework will ensure these technologies benefit society and negative impacts are mitigated.

### Programming and funding

As an emerging technology, quantum computers have different commercialization pathways than other technologies, thus requiring different supports. Quantum computing start-ups may require many years or decades of investments before they can bring a product to market. Unfortunately, the duration of funding support offered by several federal innovation programs is much shorter than the time needed to develop quantum computers. In other cases, program requirements (such as number of employees, years since incorporation, or revenue thresholds) makes it challenging to support early-stage entrepreneurs. As well, many programs are tailored towards providing loans rather than grants, which is challenging for startups. Consideration of longer funding duration, follow-up investments, cash advances, and more flexible program requirements would better support the development of quantum technologies.

Access to funding through other Canadian sources, such as venture capital, angel investors, business incubators and other forms of private equity, are critical to building a vibrant quantum ecosystem and are the largest source of funding for quantum companies. Without sufficient funding from start-up to scale-up, there is a risk that Canadian quantum companies will be acquired by foreign companies, leading to a loss of IP, talent and returns to other countries.

### Intellectual property

Encouraging Canadian quantum innovators to protect and hold the rights to their intellectual property assets will stimulate growth, encourage innovation, attract investment and protect their businesses. Innovators will need to develop a global IP protection strategy.

The [Canadian Intellectual Property Office](#) (CIPO), a special operating agency of ISED, provides online [Education, tools and resources](#) and delivers IP services in Canada. Its [Intellectual Property Advisors](#) help small-and-medium sized businesses understand the value of their IP and develop an IP strategy. Information about applying for IP rights, enforcement and commercialization, as well as relevant government programs, is also available through the [IP Village](#). Financing and tailored advisory services are available through the NRC IRAP's [IP Assist](#) program, BDC Capital's [Intellectual Property-Backed](#)

[Financing](#) and ISED's [ElevateIP](#) by way of several business accelerators and incubators targeting startups. Finally, businesses can find relevant IP assets held by Canadian public sector and not-for-profit organizations through the [Explore IP](#) database where users can easily contact IP holders to discuss and negotiate a licensing arrangement.

### Research security

Safeguarding Canada's quantum research and its resulting assets from foreign theft, interference or misuse, is essential for maintaining the country's economic stability, national security, technological advancements. Quantum research and its underlying data and resulting technologies are defined as 'sensitive research', and could be used to advance a foreign state's military, intelligence or surveillance capabilities. Sensitive research includes 'dual-use research', which refers to products, data, knowledge or technologies that have both purely scientific and military or intelligence applications. From a research security perspective, Canadian researchers may be developing or collecting knowledge or information for legitimate scientific purposes, but that information could be illicitly acquired or exploited by others with the intent to cause harm to Canada's national interests. Unauthorized access to quantum research and technology can undermine Canada's national security interests or those of its allies, including the disruption of the economy or critical infrastructure.

The Government of Canada remains committed to protecting quantum research and technologies against foreign interference, espionage and theft. Research security is a collective effort – researchers, academia, firms, funding organizations and governments have a shared responsibility to identify and mitigate any potential national security risks related to research. In consultation with the science and research community, the Government of Canada has taken several measures to protect the country's world-class research and continues to provide support and guidance for implementing research security due diligence. This includes a series of federal policies, including the new [Policy on Sensitive Technology Research and Affiliations of Concern](#), and the [National Security Guidelines for Research Partnerships](#). Other advances that support the implementation of Canada's research security policies include the establishment of a Research Security Centre, as well as \$50 million in funding through the [Research Support Fund](#) for eligible post-secondary institutions to build their research security capacity. In addition, the Government of Canada continues to release and develop new tools and resources that are available through the [Safeguarding Your Research](#) portal.

Canada is focused on ensuring that Canada's research ecosystem remains as open and internationally collaborative as possible, in alignment with its foundational principles of transparency, merit, academic freedom and reciprocity. In so doing, this enhanced security posture is meant to safeguard, but not limit, Canada's cutting-edge research by mitigating research security risks.

Security related to quantum communication and cryptography is addressed in the quantum communication and post-quantum cryptography roadmap.

### International partnerships and agreements

No country can succeed on its own. Developing partnerships with like-minded countries will improve Canadian research and commercial outcomes. Promoting the Canadian quantum sector abroad and developing partnerships can help attract talent, secure access to global supply chains, further R&D, increase exports, and advance adoption of quantum technologies. Efforts to date have included issuing joint co-operation statements with [the UK](#) and [Japan](#), and negotiation of others is underway. As well, international missions with key markets will help Canadian companies to access new markets.

## Action plan

The objective over the long-term (7+ years) is to:

- ensure Canada has a strong talent pipeline that meets industrial needs and develops a competitive framework for the attraction, development and retention of talent
- develop and maintain quantum training initiatives for continuous upskilling on new technology advancements
- to better understand and leverage our assets, capabilities and strengths, establish coordination mechanisms across the Canadian quantum computing ecosystem and with international partners
- ensure that Canada is a world leader in the global trade of quantum computing and software products and services

The action plans below indicate short (0-3 years) and medium term (3-7 years) actions to support the quantum computing ecosystem.

### Strengthen the talent pipeline

Action item	Timeline	Lead
C1. Establish dialogue between industry and academia to identify partnership opportunities and training program needs on a variety of quantum computing systems for upskilling, college, polytechnic, and undergraduate programs	Short and medium term	Academia, Industry/Non-Profit
C2. Develop upskilling programs with industry and integrate quantum computing curricula into undergraduate, masters, polytechnic and professional programs, including: <ul style="list-style-type: none"> <li>• training program for software stack along with upskilling current professionals/executives in quantum computing awareness, and current researchers/developers in quantum software technical skills</li> <li>• hardware and component development, manufacturing and operation, including for engineers and technicians</li> </ul>	Short and medium term	Academia
C3. Undertake equity, diversity and inclusion initiatives, such as the Dimensions program and the 50-30 Challenge	Short and medium term	All
C4. Coordinate among federal, provincial and territorial governments to improve training and certification/accreditation	Short and medium term	Federal, provincial and territorial governments
C5. Strengthen the attraction and retention of talent by reviewing immigration and visa processes for quantum highly qualified personnel (HQP)	Short and medium term	Government of Canada
C6. Build Government of Canada expertise on quantum computing including on adoption and usage	Short and medium term	Government of Canada

### Promote Canadian quantum computing science, technology, and industry domestically and internationally

Action item	Timeline	Lead
C7. Establish learning programs to support industry awareness and adoption of quantum computing	Short and medium term	Academia, Industry/Non-Profit
C8. Undertake outreach and marketing activities to raise awareness of quantum technologies in Canada	Short and medium term	Government, Academia, Industry/Non-Profit
C9. Establish an intergovernmental working group with representation from interested provincial and territorial governments to promote resource and knowledge sharing	Short term	Federal, provincial and territorial governments
C10. Collaborate with like-minded international jurisdictions to leverage talent, share resources, and advance quantum computing R&D	Short and medium term	Government of Canada
C11. Launch international trade missions and other activities to help Canadian firms integrate into the global supply chain, expand into new markets, improve commercial adoption, strengthen collaborations and attract international talent	Short and medium term	Government of Canada

#### Address barriers to growth for Canadian quantum computing and software companies

Action item	Timeline	Lead
C12. Provide support and advice to grow quantum businesses, including entrepreneurship training, networking with quantum researchers, companies and end users	Short and medium term	Government of Canada, Academia, Industry, Non-Profit
C13. Connect quantum companies with funders, and encouraging venture capital, angel investors, business incubators and other forms of capital to invest in the Canadian quantum sector	Short and medium term	Government of Canada, Industry, Non-Profit

#### Identify societal impacts and develop an ethics framework

Action item	Timeline	Lead
C14a. Identify societal impacts and develop ethics framework	Short term	Government, Academia, Industry/Non-Profit
C14b. Implement the ethics framework	Medium term	Government, Academia, Industry/Non-Profit

**Protect intellectual property and improve the security posture of Canadian researchers and innovators**

Action item	Timeline	Lead
<p>C15. Advance security and IP:</p> <ul style="list-style-type: none"> <li>governments raise awareness of security requirements, export control, and IP issues among the quantum computing community</li> <li>academia supports creators within academic institutions in developing IP strategies and protecting research and intangible assets</li> <li>industry strengthens security measures, implements IP strategies, protect IP rights and identifies challenges in protecting intangible assets</li> </ul>	Short and medium term	Government, Academia Industry/Non-Profit

**Provincial actions (as submitted)**

Action item	Timeline	Lead
C16. Launch and implement Alberta’s Quantum Tech Framework	Short and medium term	Government of Alberta
C17. Support global expansion/export of Alberta companies in quantum software programming	Medium term	Government of Alberta
C18. Support technology collaboration between Alberta companies and international companies in quantum computing	Medium term	Government of Alberta
C19. Attract anchor companies to Alberta to further develop and integrate the quantum ecosystem into the global value chain	Medium term	Government of Alberta
C20. Continue to develop and implement B.C.’s upskilling programs to build the quantum workforce, complementing the quantum education offered through post-secondary institutions	Short and medium term	Government of British Columbia
C21. Working with quantum experts, develop educational programs and qualifications to build B.C.’s skilled quantum workforce in target industries to assist businesses and organizations to adopt quantum solutions	Short and medium term	Government of British Columbia
C22. Engage with quantum post-secondary institutions and quantum companies to explore micro-credentials or specialized certificate programs that have a focus on quantum computing courses	Short and medium term	Government of Ontario
C23. Develop partnerships between quantum companies and universities to develop experienced talent through internships for students in the STEM fields and on-the-job training for existing technical professionals in adjacent fields who have an interest in transitioning into quantum computing sector to develop pipeline of highly skilled quantum talent	Medium term	Government of Ontario
C24. Consider creating a program that directly connects start-ups with accredited patent lawyers who can provide legal guidance and assistance in filing patents	Medium term	Government of Ontario
C25. Designate and support with consequential funding the Sherbrooke Innovation Zone DistriQ dedicated to quantum technologies, to foster innovation in quantum computing technologies and set up value chains	Short and medium term	Government of Québec



C26. Support innovation at all TRLs, from fundamental science to the commercialisation of technologies by startups and SMEs	Short and medium term	Government of Québec
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## Conclusion

Governments, academia, industry, non-profits, and citizens must work together to succeed in achieving this NQS mission. That is why the Government of Canada will continue its ongoing dialogue with stakeholders, provinces and like-minded countries, and deepen its collaborations to ensure that the elements are in place for success.

Quantum computing hardware and software are advancing rapidly. As the global context changes, we must remain flexible and ensure our roadmap and actions remain open and adaptable to innovation and swiftly changing realities, to make Canada a world leader in the continued development, deployment and use of quantum computing hardware and software—for the benefit of all Canadians.

# Annex A: Current status of quantum computing technologies<sup>4</sup>

Technology	Basic description	Advantages	Disadvantages/ challenges
<b>Ion trap</b>	Individual ions held in a vacuum via an electromagnetic trap generated by surrounding electrodes. Laser pulses perform gate operations.	Long coherence times; mature technology.	Fluctuating electric and magnetic fields push on the ions, causing decoherence. Slow gate times. Development of scalable architectures based on integrated traps.
<b>Neutral atoms and molecules</b>	Individual atoms or molecules trapped in arrays of optical tweezers. Gates are implemented with lasers pulses.	Long coherence times; scalable; tunable interactions; readily integrated into optical networks.	Relatively new technology (but rapidly developing within a mature field); gate fidelities need to be improved; requires good laser stabilization; relatively slow gate times.
<b>Photons</b>	Information encoded in polarization, orbital angular momentum, number (0/1 photons), time, or frequency modes. Information encoding and gate operations through phase shifters, beam splitters, optical media, interferometers, frequency filters. Detection through avalanche photodiode detectors (APDs), superconducting nanowire single-photon detectors (SNSNDs), single-photon avalanche detectors (SPADs).	Lack of interaction with environment reduces decoherence; mobility makes them ideal for quantum network communication; built on silicon infrastructure; robust over long-distance transmission; easy access to qudits and high information encoding; operable at room temperature.	Difficult to make photons interact with each other, which affects the implementation of quantum gates; difficult to make them interact with each other; Kerr media is absorptive and scatters light; requires precise control of large circuits of linear optical components.
<b>Emitter-photon hybrid (indirect photonic interactions)</b>	While quantum information is encoded and carried in photons, the state preparation and multi-qubit	On-demand generation and distribution of entanglement	Generating cluster states of dimension >1 generally requires using either coupled

<sup>4</sup> Resch., Salonik and Karpuzcu, Ulya R. [Quantum Computing: An Overview Across the System Stack](#). p.19

	<p>interactions e.g., two-qubit gates on photons, are realized indirectly through intermediate quantum emitters. E.g., quantum dots, and defects in nanodiamonds.</p> <p>Once a highly entangled photonic state is attained, the information processing is done through measurement-based or fusion-based quantum computing protocols, which are implemented on cluster states (state of the art with qubits, in principle extendible to qudits).</p>	<p>through the use of intermediate matter qubits, thereby eliminating the necessity of photon-photon interactions through nonlinear media.</p>	<p>emitters, which is technologically challenging, or using fusion gates, which is probabilistic in nature.</p> <p>Difficult to achieve photon indistinguishability using different emitters.</p>
<b>Photonicallly-linked spins</b>	<p>Electron and nuclear spins of defect centres in silicon or other semiconductors. Linked by optical photons and spin-photon interface.</p>	<p>Photons allow long-range interaction; spins have low decoherence and high-fidelity operations; built on silicon infrastructure.</p>	<p>Slower operations for nuclear spins; probabilistic entanglement layer.</p>
<b>Measurement-based / Fusion-based photonics quantum computing</b>	<p>Hybrid quantum computing such as measurement-based quantum computing</p> <p>For instance, quantum dots can be used to generate photonics cluster and graph states, which could then be fused together to generate larger photonics graph state and to perform large-scale quantum computing.</p>	<p>A hybrid approach tries to get the best of both worlds by using interactions in quantum dots for photon generation and low decoherence of photons due to lack of interactions with environment.</p>	<p>A hybrid approach requires high fidelity and high efficiency emission of photons and high collection efficiency. It requires indistinguishability of photons for effective fusion.</p>
<b>Quantum dot</b>	<p>Semiconductor particles a few nanometers in size down to single atom quantum dots. Can be constructed in semiconductors with controllable numbers of electrons, including 0 to 1. The spin of these electrons can be used as qubits.</p>	<p>Potential scalability with well established fabrication techniques; all electrical operation, including electrically controllable spin-spin coupling; potential high density with single atom quantum dots.</p>	<p>Decoherence due to electrostatic fluctuation; requires cryogenic conditions and additional development of atomically precise manufacturing (APM) infrastructure.</p>



<b>Solid-state spin</b>	Nuclear or electron spin of donor atoms in a semiconductor or NV centers in diamond.	Highly coherent; potential CMOS compatibility. APM gives a path towards deterministic positioning of single atom quantum memories and precision fabrication of colour centers in diamond and silicon.	High precision fabrication requirements; slower operations for nuclear spins.
<b>Superconductors</b>	Charge, current, or energy of superconducting circuit.	High compatibility with existing fabrication technique; electronic control; easy coupling; mature technology used in fault tolerant approaches.	High quality materials and nanofabrication required for high-performance devices, large physical footprint and colder temperatures required. Appropriate facilities for install/operation also required.
<b>Bosonic codes in superconductors</b>	Qubits encoded in the energy states of cavities using superconducting quantum chips.	Small or no overhead required for quantum error correction; fast computational clock speed; leverage highly performant and scalable hardware platform.	Very low error rates and fault tolerant gates possible but not yet demonstrated; access to state-of-the-art superconducting quantum chips.
<b>Topological</b>	Non-abelian anyons can be created in superconductors and topological insulators. Gates performed by braiding the anyons or by performing measurements.	Hardware level resistance to error. Synthetic photonic lattices explorable for large topological structures.	Less mature than other approaches; hard to engineer.

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<sup>iv</sup> M. P. da Silva, C. Ryan-Anderson, J. M. Bello-Rivas, *et al.* (2024). [Demonstration of logical qubits and repeated error correction with better-than-physical error rates](#).

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