National Quantum Strategy

National Quantum Strategy Roadmap

QUANTUM SENSING

Government of Canada Gouvernement du Canada

Canada

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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 sensing 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 sensors

Quantum sensors may significantly improve the accuracy, precision, sensitivity and efficiency of many different kinds of applications using the properties of quantum mechanics, such as indistinguishability, quantum entanglement, quantum interference, quantum-state squeezing and spin. Platforms for quantum sensing include using photonic, atomic, molecular, superconducting or solid state systems.

Advancements in quantum sensors can improve the precision of information, benefitting a wide variety of different sectors. For example, once fully adopted, quantum sensors will help enhance food security, agriculture and forestry, mineral exploration and extraction, infrastructure, lands and environmental monitoring, navigation and transportation safety, defence and security, and health care. Early commercial opportunities are already being exploited, with more widespread impacts expected in the next few years. By 2026, the global market for quantum sensors is projected to be nearly US$550 million.[1]

Canadian companies and research organizations have expertise in the application of sensing technologies across a number of domains. For example, Canada is a leading user of space-based remote sensing for monitoring infrastructure and environmental change.

Additionally, Canada is a world leader in atomically precise manufacturing (APM), and in the development, design and manufacturing of next generation all-silicon, ultra-low power, high-speed quantum devices and sensors. Specifically, Canada is innovating in atom-defined lithography on hydrogen-passivated silicon surfaces. Hydrogen lithography is crucial to the development of quantum devices and has already been integrated into several significant quantum efforts internationally.

Other areas in which Canada has expertise include, but are not limited to, silicon quantum dot sensing for chemical analytes, sensors based on ultracold neutral atoms and matter-wave interferometry and selective nucleic acid bio-diagnostics. Use cases for these technologies include improving detection of pollutants, diseases or underground resources; accuracy of inertial navigation systems; and advance fundamental physics research. Long-distance networking of quantum sensors is another opportunity for Canada, as it may enable enhancement of performance far beyond what is possible with individual sensor systems, including on a global scale with major implications for climate monitoring and other uses. The development of networked quantum sensors is further explored in the quantum communication roadmap.

As a world leader in quantum science, Canada can conquer the technical challenges, transition these technologies out of the lab and into the field, and lay the groundwork for a lucrative, high-tech industry.

[1] With Market Size Valued at $547.3 Million by 2026, it's a Healthy Outlook for the Global Quantum Sensors Market, Global Industry Analysts Inc., 2022.

Quantum sensing mission

Enable the Government of Canada and key industries to be developers and early adopters of new quantum sensing technologies.

To achieve this mission, the Government of Canada will explore potential areas of application for quantum sensors and encourage their adoption by supporting research and development investments to improve the performance and design of sensors and enabling technologies. The Government will also support the development of standards and efforts to make quantum sensor technologies accessible to Canadian industry more broadly.

To support the quantum sensing mission, the following priorities have been identified:

- support industry-led research and development to make sensors field deployable and usable in real world settings
- support commercialization initiatives led by incubators, accelerators and others to turn scientific breakthroughs into commercial products
- identify key receptor industries and bring together developers and end-users across industry, government and non-profit sectors to encourage adoption
- support the quantum sensing ecosystem by facilitating international collaboration, supporting talent development and attraction, identifying social considerations and strengthening research security

Programs supporting the quantum sensing mission

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

- in 2023, the Department of National Defence announced recipients for an IDEaS call on defence applications of quantum technologies
- in 2021, the National Research Council of Canada (NRC) launched the Internet of Things: Quantum Sensors Challenge program, focused on developing revolutionary sensors that use the extreme sensitivity of quantum systems to enhance measurement precision and sensitivity rates, and even expand the kinds of phenomena that can be measured
- in February 2022, Innovative Solutions Canada (ISC) launched two calls to advance quantum sensing prototypes and supporting technologies: one to support the development of a quantum-level biophoton optical imager and another to develop ultrasensitive spectroscopy systems for quantum photonics
- in June 2022, ISC launched a call to support pre-commercial quantum sensing prototypes and enabling technologies that can measure a variety of physical quantities, including electric or magnetic fields, precise timing, temperature, and chemical or biological processes

Furthermore, the Department of National Defence and Canadian Armed Forces released the Quantum Science and Technology Strategy Implementation Plan, known as Quantum 2030, in March 2023. Quantum 2030 identifies four promising quantum technologies with defence and security applications and lays out a seven-year plan to develop prototypes ready to be tested in the field by the year 2030.

Two of the technologies identified are quantum sensing technologies (quantum-enhanced radar and quantum-enhanced LiDAR).

Agriculture and Agri-Food Canada (AAFC) has specialized imaging and spectroscopy facilities to enable and lead initiatives focussing on the use of quantum sensors at microscopic scale (e.g., virus-free status of plant seeds, biofilm monitoring, plant cellular process monitoring). AAFC's network of experimental farms allows the development and testing of quantum sensors in real-world applications ranging from soil, diseases and crop monitoring (e.g. soil microbiome sensors, soil root sensing, soil water status, GHG emissions, plant disease identification). Robotic platforms and drone technologies, used in agriculture 4.0, could also benefit from novel GPS-free sensor technologies, which could be evaluated in controlled environments.

Helping Farmers Grow More Food with Less Environmental Impact: Canada is a world leader in the application of space based technology and ground based sensors for improving the monitoring and collection of data to support a sustainable agricultural sector. Advances in quantum computing and quantum sensing are expected to improve the precision of the information farmers can get and use to gain insight on their crops, soil conditions, plant health and projected yield. Combining this information with models and smart farm equipment could reduce the use of water, fuel and pesticides by enabling efficient decision making while continuing to produce a stable and affordable food supply for all Canadians.

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 the Natural Sciences and Engineering Research Council of Canada (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 (IDEaS), Deep Tech Venture Fund, etc.

1. Supporting industry-led research and development to make sensors field deployable and usable in real world settings

Quantum sensing has the potential to create disruptive changes across several application areas. The maturity level of sensing technologies varies substantially with some quantum sensors already being deployed while others are still under development. Recognizing that spreading investment to support all modalities would reduce impact, this roadmap will focus on activities that are closer to commercialization than some other technologies:

- Canadian strengths in sensing technologies that could be adopted/commercialized/mass produced in the near-term (1-5 years)

- technologies that have a base of expertise in Canada
- priority sectors of the Canadian economy where the near-term adoption of sensing technology could have a high impact (1-5 years)

Technologies which do not meet these criteria could still be supported through existing programs targeted to basic research rather than commercialization.

There are many cases where multiple sensing technologies can address the same problem. For this reason, the roadmap will express priority areas as opposed to specifying technologies. Consultations have identified six areas where Canada has a base of expertise, technologies are mature and their advancement can bring great benefit to Canadians, including:

Area	Critical mass technology area
Geographical surveying, resource exploration and environmental monitoring	• Quantum-enhanced magnetometers • Quantum-enhanced gravimeters • Optical fibre sensing for seismic activities
Biomedical and healthcare	• NMR quantum control • EPR spectroscopy
Biosensors and diagnostic tests	• Quantum light sources • Quantum nanomaterials • Quantum detectors
Position, navigation and timing	• Quantum-enhanced gyroscopes • Optical and solid state atomic clocks
Remote sensing	• Hardware in the optical domain and software for remote sensing • Superconducting sensors • Sensor arrays
RF sensing, communication and radar	• Quantum enhanced radar • Atomic vapour cells

Key challenges

Research, engineering and commercialization

Research and development efforts, such as miniaturization, prototyping and production scale-up are required to refine some types of quantum sensors to make them portable and usable by non-experts. Since there are a number of different sensor types, prioritization of investment may be required to build world leading quantum sensing capabilities in Canada. Future actions need to consider the areas of focus and investment where Canadian companies and researchers are or can lead/win on a world stage. At the same time, priorities may change, as breakthroughs in fundamental physics can result in novel quantum sensing techniques and platforms. Investments and activities will need to be nimble to reflect the rapidly evolving opportunities and challenges in this space.

Business investment in research and development is also critical to the advancement of quantum sensors. Galvanizing, coordinating and accelerating business led research for projects with long development times has historically been a challenge in Canada due to factors ranging from capital pressures to accessing expertise. Industrial research labs are also key players in the quantum ecosystem that will need to support commercial research efforts. Support could be provided for projects that are focussed on the applied research required to bring ideas to market. A special focus should also be given to research that would make quantum sensors field deployable, rather than being suitable only for a lab environment. Resource sharing schemes and leveraging partnerships with trusted allies can also help enhance technical capabilities in a cost-effective manner.

Programming and funding

Developing quantum sensors from ideation to prototype often requires three to five years at a minimum and $5-$10M per research project. To reach commercialization, additional long periods of continuous investment are required. Unfortunately, the duration of funding support offered by several federal innovation programs is much shorter than the time needed to develop quantum sensors. In other cases, the restrictive nature of program requirements (such as number of employees, years since incorporation or revenue thresholds) makes it challenging for 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 advance 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 intellectual property (IP), talent and returns to other countries.

Action plan

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

- develop new or more compatible quantum light sources, detectors and other enabling components along with optics-based quantum sensing technologies
- developing new, highly precise sensing devices, based on quantum effects, which will improve upon state-of-the-art measurement and calibration technologies
- develop commercially competitive quantum sensors across priority areas of the Canadian economy and national defence
- enable the mass production of chip-based quantum sensors

The action plan indicates short (0-3 years) and medium term (3-7 years) actions to develop quantum sensing technologies:

Develop quantum sensing technologies

Action item	Timeline	Lead
A1. Support basic and mission-driven applied research to develop quantum sensing such as: • compatible quantum light sources, detectors and optics based sensors • chip-based sensors • quantum nanomaterials • commercially relevant sensors in priority areas to improve performance and cost effectiveness of systems	Short and medium term	Government of Canada

A2. Support the scaling up of relevant technologies	Medium term	Government of Canada
A3. Support and undertake the testing of cost, performance and/or energy advantage	Medium term	Government of Canada, industry/non-profit
A4. Undertake R&D to support quantum sensors, including on: • non-classical states (e.g. squeezed light) optical interferometry and microscopy • atom and molecular based sensors including spin-atomic and Rydberg systems • quantum material platforms (e.g. diamond NV-centers, SiC, hBN, Transition metal dichalcogenides, quantum dots) • trapped ions for quantum sensing • superconducting sensor arrays and on-chip imaging spectroscopy • cold-atom and matter-wave interferometry systems (e.g., gravimeters, gyroscopes, gradiometers, metrology) • warm atomic vapor systems (e.g. magnetometers, clocks)	Short term	Government of Canada, industry/non-profit, academia
A5. Undertake R&D to support quantum sensors, including on: • solid-state spin systems • trapped ions and neutral atoms for quantum sensing • single-electron transistors • opto-electro-nano mechanics • very large distance interferometry • robust quantum photon sources (e.g. on-demand single photon sources) • sensing qubit control electronics • trapped ions for quantum sensing • superconducting sensor arrays • cold-atom and matter-wave interferometry systems (e.g., gravimeters, gyroscopes, gradiometers, metrology) • warm atomic vapor systems (e.g. magnetometers, clocks)	Medium term	Government of Canada, industry/non-profit, academia

Provincial actions (as submitted)

Action item	Timeline	Lead
A6. Support the development of quantum sensing technologies to address productivity challenges in core sectors like agriculture, life sciences and energy	Short and medium term	Government of Alberta
A7. Launch and implement Alberta's Quantum Tech Framework	Short and medium term	Government of Alberta
A8. Continue to support advancements in quantum research and development in BC, and promote targeted industry investment into quantum sensing technology and application development	Short and medium term	Government of British Columbia
A9. Support companies working in sensing technology through programs tied to critical sectors such as Agtech, mining and advanced manufacturing	Short and medium term	Government of Ontario

A10. Support prototyping and testing facilities accessible to startups and academics, at the Institut interdisciplinaire d'innovation technologique (3IT) and the DevTeQ laboratory at the Sherbrooke quantum innovation zone	Short and medium term	Government of Québec

2. Supporting commercialization initiatives led by incubators, accelerators and others to turn scientific breakthroughs into commercial products

Several initiatives can be undertaken to support the commercialization of quantum sensing technologies. These initiatives will also address issues identified in the other roadmaps.

Key challenges

Infrastructure

Scaling up the production of quantum sensors may require access to special infrastructure such as fabrication facilities. Given the high costs of development and limited funds, it is imperative to start-ups and small and medium enterprises (SMEs) to have access to low-cost fabrication services, such as multi-project wafers, during the development cycle and be able to produce high-quality sensors when the technology is ready for commercialization. There is currently a shortage of these facilities in Canada. Developers typically run an iterative design process to test refined models before proceeding to mass production. Access to fabrication facilities could benefit this iterative process as well. The government could consider support to establish or enable access to shared infrastructure facilities for use by academia, non-profits and industry, as this will help reduce barriers to research and development.

Currently, fabrication of quantum sensors components mostly occurs at university fabrication facilities. However, these facilities do not have enough resources to fabricate at the scale necessary to enable start-ups to develop and commercialize quantum devices. There is an opportunity to support the development and transfer of mature processes from university labs to non-academic fabrication facilities, including existing fabs such as the C2MI, Canadian Photonics Fabrication Centre, Applied Nanotools etc. or new fabs.

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 sensing components. In cases where key components are only available internationally, establishing agreements to secure Canadian access may be necessary.

Enhancing our comprehension of the global supply chain and determining Canada's role within it will be necessary.

Securing supply chains

It will be necessary to procure, secure and expand upon domestic and international reservoirs of the raw materials needed for developing quantum technologies. This may include working with trusted allies to secure access to materials not available domestically for quantum applications and identifying quantum material resources within Canada to facilitate access via trusted industrial partners. New quantum materials may also lead to scientific breakthroughs, enabling novel quantum systems.

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 modalities are becoming increasingly restricted and expensive. Neon gas is a critical component in semiconductor production that is also becoming inaccessible.[2] Expanding access to alternative sources of purified silicon and neon gas is critical to scaling these technologies.

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.

Action plan

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

- engage broader Canadian industry beyond first-movers on adoption of quantum sensors
- support commercialization and scale-up of Canadian quantum sensor solutions
- encourage Government of Canada adoption of quantum sensors

The action plans below indicate short (0-3 years) and medium-term (3-7 years) actions to commercialize quantum sensing technologies.

[2] Expert Panel on the Responsible Adoption of Quantum Technologies. Quantum Potential. Council of Canadian Academies (2023).

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

Action item	Timeline	Lead
B1. Advance security and IP: • governments raise awareness of security requirements, export control and IP issues among the quantum community • academia supports creators within academic institutions in developing IP strategies and protecting research and intangible assets • industry strengthens security measures, implements IP strategies, protect IP rights and identifies challenges in protecting intangible assets	Short and medium term	Government, academia, industry/non-profit

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

Action item	Timeline	Lead
B2a. Match most pressing Canadian industry needs to existing infrastructure, and scope out further potential investments (e.g. foundry, fabrication etc.)	Short term	Government of Canada, industry/non-profit
B2b. Assess establishing, with mix of public/private funding, national infrastructure for production of quantum components	Medium term	Government of Canada, industry/non-profit
B3. 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
B4a. Identify key supply chain gaps	Short term	Industry/non-profit
B4b. Plan and begin establishing supply chains for key components, such as cryogenic systems	Medium term	Industry/non-profit
B4c. Protect quantum system supply chain and access to internationally-produced materials and technologies with international agreements	Short and medium term	Government of Canada

Provincial actions (as submitted)

Action item	Timeline	Lead
B5. Enhance existing infrastructure and capabilities in fabrication and packaging to support quantum sensing prototyping	Short and medium term	Government of Alberta
B6. Promote opportunities that enable BC companies working on quantum sensors and sensing technology 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

B7. Support the streamlining of the Intellectual Property Ontario (IPON) program, with a focus on quantum technology support for start-up companies with accredited patent lawyers to file patents	Short and medium term	Government of Ontario
B8. Support a Québec-based quantum hardware supply chain at the Centre de Collaboration MiQro Innovation (C2MI) in Bromont and the Institut National d'Optique in Québec City, with microfabrication capabilities for semiconductor and superconductor-based devices, and for integrated photonics	Short and medium term	Government of Québec
B9. Support the Quantum Venture Studio (QV Studio) based in the Sherbrooke innovation zone DistriQ, the first venture studio entirely dedicated to coaching and enabling emerging startups in the quantum sector	Short and medium term	Government of Québec
B10. Support Quantacet, a $20M Québec-based investment fund dedicated to quantum technologies	Short and medium term	Government of Québec

3. Identifying key receptor industries and bringing together the developers of quantum sensors and end-users across industry, government and non-profit sectors to encourage adoption

Key challenges

Market development and engaging end-users

Engaging with end-users will help develop a domestic market for quantum sensors, leading to further investments. This engagement will also help direct R&D to commercially relevant areas, improving possibility for commercialization and raise awareness of the importance of adoption of quantum sensors among end-users.

While more work needs to be done to identify novel application areas, quantum sensing has the potential or is already having an impact in a variety of areas:

- **Natural resources:** Discovery and exploration of critical minerals, thus providing high-accuracy and high-fidelity data to make informed decisions/monitoring of natural resources and critical infrastructures.

- **Biomedical and healthcare**[3]**:** New diagnostic tools that can detect health disorders such as cancer or dementia with more precision, earlier or in a less invasive way, leading to improved patient outcomes.
- **Biosensors and diagnostic tests:** Sensor technologies that can be used in low-cost settings, for point-of-care diagnostics or environmental sensing in remote areas to directly benefit different end-users and communities.
- **Transportation:** Improved position, navigation and timing capabilities can enable reliable navigation in new environments on land, in space and under water, potentially leading to improved transportation safety and efficiency, and autonomous vehicles.
- **Defense:** Quantum-enhanced radar and LiDAR systems have the potential to enable detection of stealth objects and improve imaging resolutions, including underwater imaging.
- **Food security:** Currently identified challenges in food security and productions could foster the development of new quantum sensors aligned with the Canadian agrifood sector regulatory requirements.

Adoption

There is relatively low awareness and adoption of quantum sensing technologies among Canadian industries, despite the commercial availability of some quantum sensors. Work with the Council of Canadian Academies[4] and Statistics Canada will provide more information on the barriers and opportunities for adoption of quantum technologies. Adoption of quantum sensing technologies by key Canadian receptor industries will be paramount to success, along with exports to international markets.

To improve uptake, existing business collaborations and public-private partnerships should be leveraged to promote sensing technologies, for example, focussing on high value crops in agriculture where investments in advanced data collection have proved profitable during initial phases of technology development. Engaging with senior executives in end-user organizations to expose and educate them to the benefits of quantum technologies, such as through targeted training, will allow them to make informed decisions. Programs that de-risk the adoption of quantum technologies or provide lower cost access to infrastructure and personnel will incentivize adoption.

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

The application of geo-spatial technologies in Canada is linked to the development and application of space based remote sensing technologies (e.g. Canadian Space Agency, NASA, EU Copernicus, European Space Agency, Group on Earth Observations). Multi-party discussions in these areas, such as through the Committee on Earth Observation Satellites (CEOS), may help identify user needs across a wide spectrum of communities in both private and public sectors.

Canada is also a leader in the development and application of sensing technology in agriculture through the networks of Smart Farms and educational institutes promoting the uptake of these technologies, and these can be leveraged to support adoption.

[3] Aslam, N., Zhou, H., Urbach, E. K., Turner, M. J., Walsworth, R. L., Lukin, M. D., & Park, H. (2023). Quantum sensors for biomedical applications. *Nature Reviews Physics*, *5*(3), 157–169.
[4] Expert Panel on the Responsible Adoption of Quantum Technologies. Quantum Potential. Council of Canadian Academies (2023).

Action plan

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

Action item	Timeline	Lead
C1. 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 scope requirements with end users, refine value proposition and technical requirements, etc.	Short and medium term	Government, academia, industry/non-profit
C2. Identify relevant use cases/proof of value with near- and long-term impact and support proof of concept projects in Government of Canada departments/agencies	Short and medium term	Government of Canada
C3. Assess funding proof-of-concept projects on uses of quantum sensors 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
C4. Assess: • investing in pilot projects and sandboxes where end-users from industry and government can test applications • supporting programs with full design-fab-test cycles	Short and medium term	Government of Canada
C5. Engage Canadian and international end-users to work with quantum sensing developers to test sensing technologies	Short and medium term	Government of Canada, industry/non-profit

Raise awareness of quantum sensing capabilities to promote adoption

Action item	Timeline	Lead
C6. Leverage industry associations to develop linkages with entire industries, like mining or energy (CIM, Pathways Alliance-COSIA) and raise awareness of quantum sensing capabilities	Short and medium term	Government of Canada/ industry/non-profit
C7. Government of Canada tests and considers adopting quantum sensors, using existing programs and mechanisms	Short and medium term	Government of Canada

Develop standards and participate in international standardization processes

Action Item	Timeline	Lead
C8. 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 of Canada/ industry/non-profit

C9. Develop and review applicable standards and regulations to ensure safety and security while minimizing regulatory burden	Short and medium term	Government of Canada
C10. Assess support for metrology activities to support the commercial ecosystem.	Short and medium term	Government of Canada

Provincial actions (as submitted)

Action item	Timeline	Lead
C11. Launch and implement Alberta's Quantum Tech Framework	Short and medium term	Government of Alberta
C12a. Support the development of quantum sensing technologies to address productivity challenges in core sectors like agriculture, life sciences and energy	Short term	Government of Alberta
C12b. • Integrate Alberta's quantum sensing industry into the global value chain so that quantum sensors are manufactured in Alberta • Support Alberta's core industries to promote quantum adoption in Alberta	Medium term	Government of Alberta
C13. Work with B.C.'s quantum companies and industry sectors to identify and raise awareness of opportunities and impacts from quantum sensing technology, and help test proof-of-concept projects to build knowledge and experience of quantum applications to advance industry adoption	Short and medium term	Government of British Columbia
C14. In collaboration with companies, non-profits, and institutions, increase awareness of quantum sensing capabilities and establish connections with Agtech, mining, and life sciences sectors, with a focus on sensing	Short and medium term	Government of Ontario
C15. Support collaborative academic-industrial projects and partnerships in strategic sectors where quantum is poised to have an impact in the near-term	Short and medium term	Government of Québec

4. Supporting the quantum sensing ecosystem

Key challenges

<u>Attraction, development and retention of a quantum workforce</u>

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 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 it 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 technologies may impact many sectors of the economy. It will be necessary to identify social implications and ethical considerations. This could include:

- use of sensing technologies in public settings that could impact privacy or human rights
- development and 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 impacts of quantum sensors, encompassing both the effects of improved climate monitoring and environmental impacts of quantum sensor components and materials

Learning from ethical issues and regulations in artificial intelligence (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.

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 and 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 such as 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 posture is meant to safeguard, but not limit, Canada's cutting-edge research by mitigating research security risks.

International partnerships and agreements

No country can succeed by doing it alone. 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

Strengthen the talent pipeline

Action item	Timeline	Lead
D1. Establish dialogue between industry and academia to identify partnership opportunities and training program needs for upskilling, college, polytechnic, and undergraduate programs	Short and medium term	Academia, industry/non-profit
D2. Support job integrated learning and on-the-job training	Short and medium term	Government of Canada, industry/non-profit
D3. Develop upskilling programs with industry and integrate quantum sensing curricula into undergraduate, masters, polytechnic, and professional programs, including: • training programs along with upskilling current professionals/executives in quantum sensing awareness	Short and medium term	Academia

• hardware and component development, manufacturing and operation, including for engineers and technicians		
D4. Undertake equity, diversity, and inclusion initiatives, such as the Dimensions program and the 50-30 Challenge	Short and medium term	All
D5. Coordinate among federal, provincial and territorial governments to improve training and certification/accreditation	Short and medium term	Federal, provincial and territorial governments
D6. Strengthen the attraction and retention of talent through reviewing immigration and visa processes for quantum highly qualified personnel (HQP)	Short and medium term	Government of Canada
D7. Build Government of Canada expertise on quantum sensing including on adoption and usage of quantum sensors	Short and medium term	Academia, industry/non-profit

Address barriers to growth for Canadian quantum sensing companies

Action item	Timeline	Lead
D8. Provide support and advice to grow quantum businesses, including entrepreneurship training, networking with quantum researchers and companies and end users	Short and medium term	Government of Canada, academia, industry/non-profit
D9. Connect quantum companies with funders and encourage 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

Promote Canadian quantum sensing science, technology, and industry domestically

Action item	Timeline	Lead
D10. Establish learning programs to support industry awareness and adoption of quantum sensing	Short and medium term	Academia, industry/ non-profit
D11. 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
D12. Collaborate with like-minded international jurisdictions to leverage talent, share resources and advance quantum sensing R&D	Short and medium term	Government of Canada
D13. Launch international trade missions and other activities to help Canadian firms integrate into the global supply chain, improve commercial adoption, strengthen collaborations, expand into new markets and attract international talent	Short and medium term	Government of Canada
D14. Promote Canadian quantum sensing technologies domestically and internationally to trusted allies	Short and medium term	Government of Canada

Identify societal impacts and develop an ethics framework

Action item	Timeline	Lead
D15a. Identify societal impacts and develop ethics framework	Short term	Government, academia, industry/non-profit
D15b. Implement the ethics framework	Medium term	Government, academia, industry/non-profit

Provincial actions (as submitted)

Action item	Timeline	Lead
D16. Launch and implement Alberta's Quantum Tech Framework	Short and medium term	Government of Alberta
D17. Support training, attraction, and retention of HQP in quantum sensing research	Short term	Government of Alberta
D18. Support work-integrated learning programs where quantum sensing can drive increased productivity in Alberta's core industries like agriculture and energy	Medium term	Government of Alberta
D19a. Drive the development of trans-disciplinary solutions that address global challenges through the application of quantum technologies	Short term	Government of Alberta
D19b. Accelerate industry-academic collaboration in quantum sensing	Medium term	Government of Alberta
D20. Support technology collaboration between Alberta companies and international companies in quantum technologies	Medium term	Government of Alberta
D21. Attract anchor companies to Alberta to further develop and integrate the quantum ecosystem into the global value chain	Medium term	Government of Alberta
D22. 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
D23. Promote initiatives (like the Integrated Marketplace) that support government, industry and academic collaboration to grow quantum sensing technology and create a robust quantum sector	Short and medium term	Government of British Columbia
D24. Leverage the Business Immigration Services team pathways and the Global Express Entry program to focus on filling labour shortages with experienced global talent acquisition for both Technical and Vertical industry talent	Short and medium term	Government of Ontario
D25. Establish and cultivate partnerships between postsecondary institutions and quantum companies focused on sensing to provide internships for students in STEM fields and on-the-job training for technical professionals with a focus on energy, Agtech and mining	Short and medium term	Government of Ontario

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 sensing is advancing rapidly both in Canada and around the world. As the global context changes, Canada must remain flexible and adapt our roadmap and actions to enable the Government of Canada and key industries to be developers and early adopters of new quantum sensing technologies.