National
Quantum Strategy
CONSULTATIONS

What We Heard

REPORT

Government of Canada Gouvernement du Canada

Canada

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Executive summary

BUDGET 2021 ALLOCATED $360 MILLION IN investments over seven years to launch a National Quantum Strategy (NQS). In order to move forward to develop and implement the NQS, Innovation, Science and Economic Development Canada (ISED) held a series of roundtables with key stakeholders to better understand the challenges and opportunities facing firms, institutions and organizations in the quantum sector. Each roundtable addressed one of the following three pillars of the NQS: research, commercialization, and talent; or the theme of security or international. In parallel, public input was sought via an online survey and a dedicated email address for stakeholders to provide input to the NQS Secretariat.

Seventy stakeholders from large and small business, industry associations, not-for-profits, and universities and colleges across Canada attended the roundtables. More than 240 individuals submitted anonymous input via the online survey and email. This report provides a summary of input gathered throughout the consultation process held from July to October 2021. The report does not attempt to interpret respondents' feedback or translate it into policy solutions, but rather, to reflect it as it was articulated.

The following overarching findings emerged regarding the NQS and the quantum sector in Canada:

- The time to act is now, across all fronts, including research, talent, commercialization, international and security.
- Talent is critical, as we are facing strong international competition to recruit and retain talent.
- It is premature to pick winners at this stage in quantum's development, but large investments are required.
- The overall amount of NQS funding may be insufficient to achieve our goals, especially as other countries have promised to invest more.
- Improved communications (including a branding strategy) are important to convey the advantages of studying, doing research and operating a business in Canada.
- Engagement with end-users and consumers is needed to build awareness and address concerns around adoption of quantum technologies.
- Domestic and international collaboration are essential for Canada to remain a leader in quantum.
- Canada's domestic market is small, so we need to connect with researchers and businesses in other countries right from the start.

In addition, findings emerged regarding issues specific to the NQS pillars and themes:

- **Research** – the importance of alignment of efforts; sequencing of NQS activities; and equitable access to quantum technologies.
- **Commercialization** – potential application areas; approaches to advance adoption of quantum technologies; the need to nurture a quantum ecosystem in Canada; and scale-up of quantum commercial activity.
- **Talent** – the importance of addressing education and training; equity, diversity and inclusion in the quantum workforce; skills challenges; and the translation of knowledge beyond the quantum sector.
- **Security** – the urgency of laying the groundwork for quantum security; promoting adoption of security solutions; capitalizing on areas of commercial opportunity; and securing supply chains.
- **International** – related findings are woven into all sections, due to the nature of the international theme.

Other findings related to the societal and ethical considerations of quantum technology, the establishment of an advisory body, intellectual property (IP) considerations and the importance of participating in the development of international standards for quantum technologies.

Introduction

BACKGROUND

QUANTUM SCIENCE IS THE STUDY, manipulation and control of systems at the atomic and subatomic level. Recent advances in the field have enabled greater control of systems to perform complex tasks with higher precision.

As an enabling platform, quantum can lead to major advances in related fields, such as computing, sensing, secure communications and advanced materials. However, quantum computing could also bypass current encryption standards and undermine the security of the digital economy.

Quantum has the potential to grow the economy and create jobs. A study commissioned by the National Research Council of Canada (NRC) in 2020[1] estimates that the total economic impact of quantum technologies in Canada by 2025, including indirect and induced effects, will be $533 million, with 1,100 jobs and $188.3 million in returns. In 2045, quantum is expected to be a $138.9 billion industry, with 209,200 jobs and $42.3 billion in returns.

Earlier investments by private and public sectors, including more than $1 billion invested by the Government of Canada between 2009 and 2020, has helped to produce a highly skilled research and development (R&D) community in quantum technologies. Canada's growing quantum sector currently includes more than 100 ecosystem players, including companies, research labs, academic institutions, accelerators and incubators. The sector's capacity stretches across Canada and spans several quantum science specializations.

Budget 2021 allocated $360 million in investments over seven years to launch a National Quantum Strategy (NQS). The strategy will:

- amplify Canada's significant strength in quantum research;
- grow our quantum-ready technologies, companies and talent; and
- solidify Canada's global leadership in this area.[2]

1 Update of the 2017 Report: Quantum Canada: Socio-Economic Impact Assessment, Doyletech, 2020

2 Budget 2021: A Recovery Plan for Jobs, Growth, and Resilience (Launching a National Quantum Strategy on page 149 of PDF version)

The budget committed to a Gender-based Analysis Plus (GBA+) responsive approach to proactively reduce barriers to participation by considering equity, diversity and inclusion as the strategy is further developed and implemented.[3] An NQS Secretariat at Innovation, Science and Economic Development Canada (ISED) will coordinate the strategy.

CONSULTATIVE PROCESS/METHODOLOGY

ISED and other federal departments and agencies have been engaging in ongoing conversations with the quantum sector over several years. In addition, the Chief Science Advisor of Canada, Dr. Mona Nemer, convened a group of domestic and international stakeholders in spring 2021. To build on this foundation, in July 2021, ISED initiated consultations on the NQS through a series of virtual roundtables, an online survey and a dedicated email address for stakeholders to provide input to the NQS Secretariat.

Roundtables

Between July 20 and August 5, 2021, ISED held a series of five invitational roundtables, which brought together key stakeholders to help the department better understand the challenges and opportunities facing firms, institutions and organizations in the quantum sector. Participants were selected to be representative of stakeholders active in quantum science or knowledgeable about the sector, including a mix of participants from large and small business, industry associations, universities and colleges, and different regions. Seventy participants attended the roundtables.

At each virtual roundtable, participants focused on one of three NQS pillars: research, commercialization or talent; or on the theme of security or international. A background engagement paper, including a set of common questions and additional questions specific to the pillar or theme, was shared with participants before each roundtable. The common questions, shown in the Annex, matched the questions in the online survey.

Discussions at each of the roundtables overlapped with other pillars and themes due to the cross-cutting nature of the topics. Input was collected without attribution to the individual participants or their organizations. Participants were encouraged to provide any additional comments to the NQS Secretariat.

Online survey and email

In parallel to the roundtables, ISED conducted a public online survey through the National Quantum Strategy website. Input was collected from July 20 to October 8, 2021, analyzed and included in this report. More than 240 participants provided anonymous input to the Secretariat via the online survey or the NQS email address.

Findings

The NQS Secretariat and ISED's Public Opinion Research, Strategic Communications and Marketing Sector analyzed the feedback from the roundtables, responses to the online survey and email input, and identified some overarching recommendations, information and considerations that apply to all pillars and themes. These are captured under "overarching findings" and are also discussed in greater detail as they relate to each pillar and theme. In addition, advice, information and considerations unique to each pillar or theme are discussed in the appropriate section.

This report does not attempt to interpret respondents' feedback or translate it into policy solutions, but rather, to reflect it as it was articulated. Any corrections can be brought to the attention of the NQS Secretariat.

3 Annex 5: Budget 2021 Impacts Report (Launching a National Quantum Strategy on page 496 of PDF version)

Overarching findings

A NUMBER OF OVERARCHING ISSUES emerged across the roundtables and were reinforced by the online survey results. Participants indicated that addressing these issues should be central to the NQS, and that the strategy should be a living document that can evolve along with the rapidly developing quantum landscape.

The time to act is now, across all fronts: research; talent; commercialization; international and security.

The quantum field is developing rapidly. Canada needs a coherent and coordinated strategy to remain a leader in quantum research, develop the workforce, business environment and infrastructure to support commercialization, and be prepared for the challenges quantum may pose for traditional cryptography and data security.

Talent is critical, as we are facing strong international competition to recruit and retain talent.

Canada must not only strive to retain the top talent it produces in quantum research, but must also attract foreign talent and foster and train the diverse workforce that quantum technologies will require across many sectors.

It is premature to pick winners at this stage in quantum's development, but large investments are required.

By taking a long-term approach to the quantum sector and applying appropriate foresight and secure funding, Canada can nurture an ecosystem that will allow innovation to thrive and transition from research to commercial application.

The overall amount of NQS funding may be insufficient to achieve our goals, especially as other countries have promised to invest more.

Supporting a collaborative quantum environment that builds on our strengths and strategic investments will position Canada strategically to compete with larger international players.

Improved communications (including a branding strategy) are important to convey the advantages of studying, doing research and operating a business in Canada.

Addressing the lack of awareness of Canada's quantum capabilities among students, domestic and foreign investors, and industry will help to drive workforce development, investment and sector growth. Canada's reputation as a trusted partner and supporter of diversity and inclusiveness also represents an opportunity to help build the Canadian brand.

Engagement with end-users and consumers is needed to build awareness and address concerns around adoption of quantum technologies.

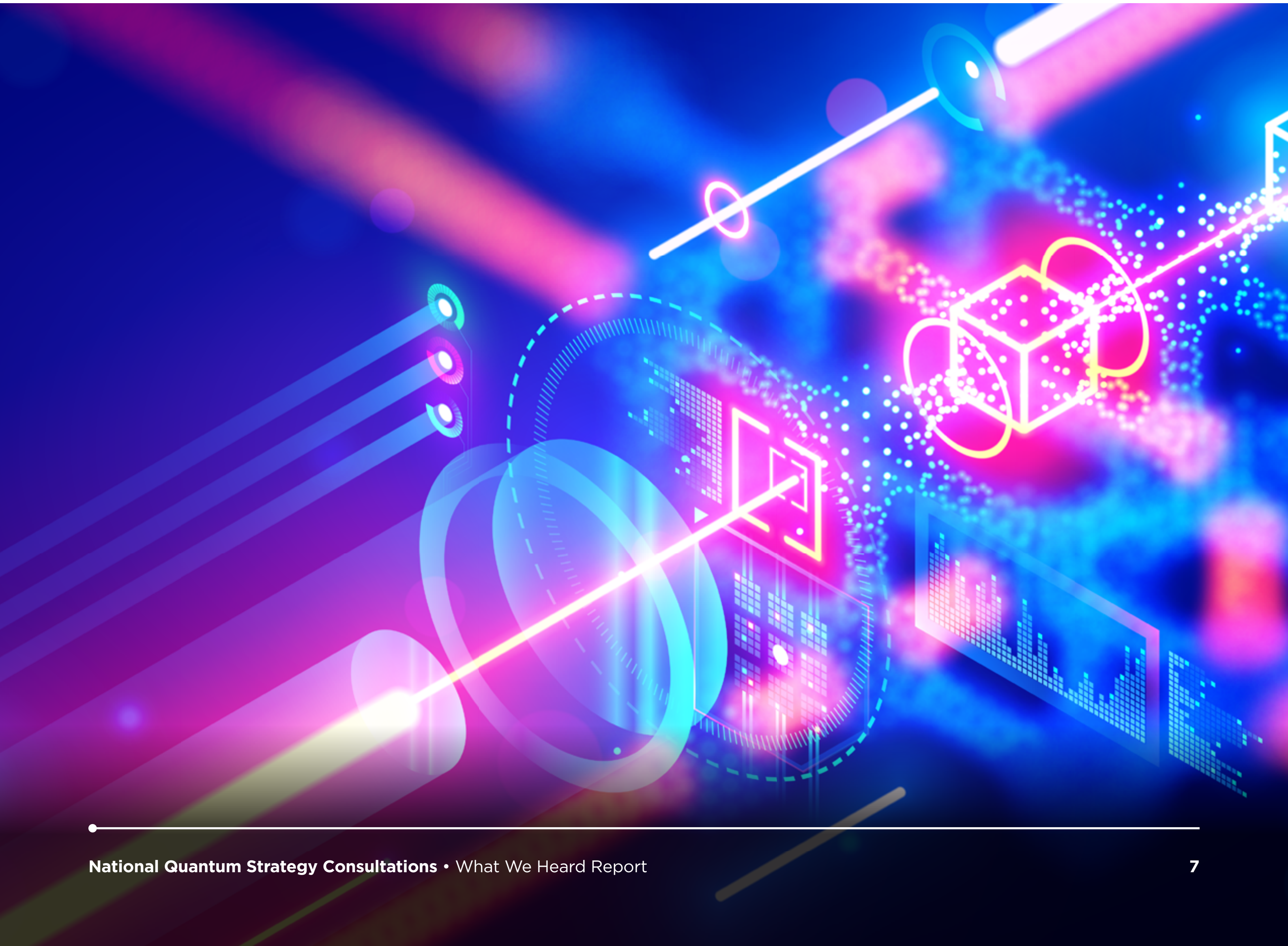
Early engagement with end-users will encourage collaboration between academia, industry and government, help to target application development and support commercial adoption and acceptance of quantum technologies.

Domestic and international collaboration are essential for Canada to remain a leader in quantum.

To form a dynamic domestic sector for quantum technologies and to compete internationally, we must coordinate and mobilize the results of Canada's scientific excellence. This will require collaboration between academia, industry and government.

Canada's domestic market is small, so we need to connect with researchers and businesses in other countries right from the start.

Canada has been a leader in quantum research, but to compete successfully in the quantum marketplace, we must look to international collaboration, foreign talent and investment, and export to international markets.



Research pillar findings

ROUNDTABLE PARTICIPANTS characterized quantum as a developing field in which research activity continues to be fundamental, with Canada leading in multiple areas of specialization. The **overarching findings** that resonated most under the research pillar included:

- a sense of urgency to act now lest Canada lose its advantage;
- pressure from international competition for top students and researchers;
- the need for longer-term funding;
- a desire for increased collaboration between academia and industry; and
- the importance of establishing international partnerships.

As with the other pillars and themes, there was consensus that **now is the time to act**. Canada needs to continue to pioneer research and accelerate its application or we risk losing the talent base that exists across Canada and our competitive advantage.

One key area for action is retaining talent, which will be critical to maintaining Canadian leadership in quantum innovation. Participants warned that Canada's quantum research capacity could be eroded as highly qualified personnel (HQP) are lost to other countries. Participants suggested that increasing university faculty positions, encouraging faculty hybrid arrangements with industry, better funding for postdoctoral and research scientists and establishing dedicated federal quantum fellowships could help to compete with other countries. (The development and retention of quantum expertise is also covered in the Talent section of this report).

Rather than directing funding to specific technologies or applications at this point, **the strategy should support many options**, while identifying and filling strategic research gaps for both short-term and long-term horizons. There was consensus that basic and applied research should be supported in parallel, and that the NQS should not lose sight of the discovery value of basic research.

Participants noted that the entire funding announcement for the NQS is less than some recent venture capital investments in individual quantum companies in the U.S. Nevertheless, a **longer-term funding commitment will make Canada more attractive amid international competition**. Since Canada cannot compete with other countries or multinational corporations on overall spending, the NQS should develop quantum capabilities by enabling a cooperative quantum ecosystem that functions collaboratively rather than competitively. Further, by envisioning where Canada's quantum sector should be in 10 years, we can establish and reinforce, through funding, the necessary discovery mechanisms now.

There was consensus that funding fewer projects across a greater number of areas would align with Canada's broad expertise. Targeted funding to mobilize a "moonshot" was also suggested. (See application areas for quantum technologies in the Commercialization section for suggestions on candidate areas for funding.)

Participants also identified some specific programs and funding mechanisms they felt could be made less restrictive or expanded, including the Strategic Innovation Fund (SIF) and NRC's Industrial Research Assistance Program (NRC-IRAP). For example, greater recognition and support of research costs, international collaborations and in-kind contributions would enhance support for researchers transforming quantum ideas into commercial products. Some programs of the Natural Sciences and Engineering Research Council of Canada (NSERC) were seen as best practices from a research perspective. It was suggested that the NQS could build on the success of NSERC's Collaborative Research and Training Experience (CREATE) and Alliance programs.

Engaging with potential users of quantum technologies will help to guide R&D efforts. Participants suggested looking to industry problems that quantum can solve and at opportunities where quantum can be coupled with other areas of Canadian strength. Improving quantum literacy among potential users, including executives, will also be important for increasing awareness, understanding and, ultimately, adoption of quantum technologies.

While continuing to support individual researchers, **support for collaboration is also needed** to integrate and build on Canada's regional strengths and collaborations to create a robust national ecosystem. Fostering collaboration between not only industry and academia, but also government and academia (e.g. the NRC sensor program) and among government labs will be necessary to move quantum forward on all fronts.

Online input echoed what was heard in the roundtables, with suggestions along several collaboration threads and tools:

- **Academic** – launch a flagship quantum research centre associated with multiple Canadian universities (e.g. TRIUMF, Canada's particle accelerator centre) and leverage multidisciplinary research.
- **Geographic** – both domestically, across provinces, where distributed research teams could collaborate without relocating, and internationally, where Canadians could work with G7 partners on a focused number of proofs of concept.
- **Thematic** – including aligning and applying quantum technologies to challenges unique to Canada, to industrial problems with a realistic return on investment and toward national grand challenges designed to build bridges between various national hubs rather than foster competition.
- **Alternative tools** – an interactive network across the innovation pipeline.

To enhance research collaboration, Canada can establish **international agreements** to cooperate in big science initiatives and strategies to take advantage of infrastructure and lessons learned elsewhere in the world. European funding calls from bilateral partners such as the U.K., the European Commission's Horizon Europe, the European Union's Quantum Flagship Program and Eureka (a European intergovernmental network for cooperation in R&D), offer a way to collaborate with international partners. Canada could consider providing dedicated funding to support collaboration for intramural and extramural researchers and private sector enterprises.

Investing in joint PhD and fellowship programs internationally, supported by international agreements, will build expertise and awareness of Canadian research. Canada can also reduce hurdles for international students to work here and strive to retain them. Facilitating the transition from postdoctoral to academic posting would provide candidates with opportunities in Canada.

Among the **findings specific to research** are the need to: align and sequence efforts; and ensure equitable access to quantum technologies both now and in the future.

To build on the leading role Canada has played in many aspects of quantum research, it was proposed that the NQS should take a long-term view, **align efforts** across national and provincial strategies and improve interagency communications and planning, as well as commercialization efforts. The government should foster an environment that supports breakthrough research across a variety of organizations and support enabling technologies such as photonics and cryo-computing.

While Canada's research strengths have helped to fuel the country's success in quantum to date, it may be vital to strategically aim for a balance between the stages of research (i.e. from early-stage exploratory research to later-stage applied research that is closer to commercialization) in the future. Each of these stages has its own requirements for talent, infrastructure and funding.

In terms of **sequencing**, it is important to get users involved in identifying problems from the start and to develop the engineering to make the most of completed research in parallel with ongoing research efforts.

Feedback from the roundtables and online survey highlighted the importance of taking steps to **ensure open, equitable access to quantum technologies**, including quantum computers, for Canadian researchers and entrepreneurs, so no one is excluded. Models suggested included IBM's Quantum Network at the Université de Sherbrooke, the B.C. Quantum Algorithms Institute and an approach similar to that of Abu Dhabi's Technology Innovation Institute.

The need to support contributors beyond the major hubs and strive to be inclusive of widely distributed expertise was also expressed.

Commercialization pillar findings

QUANTUM TECHNOLOGIES ARE EXPECTED to impact many sectors of the economy, increasing industrial capabilities and competitiveness through the development of novel products and services, and creating new vulnerabilities (e.g. in computer systems and communications). Considering the potential of quantum technologies, the early stage of their development and Canada's head start, the **overarching findings** related to commercialization include:

- timing and sequencing considerations;
- evolving talent needs;
- the need for broad-based support and funding of technologies now to build a Canadian brand and for early user engagement to advance adoption;
- the role of industry-academic collaborations; and
- the need for an international view to expand markets.

While some quantum technologies have longer time horizons in terms of bringing commercial products and services to market, others, such as quantum sensors, are expected to have commercial products in the next three to five years. With this in mind, the runway to prepare is short. **Canada needs to move ahead on all fronts and not wait for technologies to be fully developed**. We need to act quickly in supporting collaboration between industry and academia to continue to seed future commercialization.

To apply quantum to business needs, companies require quantum-literate staff who can translate concepts and research into useful ideas. Skill sets, such as systems analysis, engineering and business expertise, will become important as quantum moves toward commercialization. The presence of quantum-knowledgeable employees in a wide variety of companies and industries will support the acceptance and adoption of new technologies. Retaining and attracting both talent and companies are key to being competitive internationally. (This issue is covered in greater detail in the Talent section.)

When addressing support for quantum companies, there was consensus that **government should remain inclusive and not pick winners at this time,** as quantum is a developing sector. At some point, Canada will need to make a strategic decision whether to support a few large players or projects, or many small ones.

It was noted that Canada has a history of producing excellent research that often does not get commercialized. **Lack of capital was identified as the biggest single threat to Canadian quantum leadership**. Participants described a greater appetite in the international marketplace to invest in quantum. Matching Canadian quantum companies with international venture capital and encouraging international start-ups to create Canadian subsidiaries could help to address this issue. Israel and India were cited as examples of countries that have attracted local branches of major international venture capital groups. Participants suggested that government can also remove hurdles that deter international firms from doing business in Canada. However, we should ensure that foreign investment does not translate into foreign ownership.

While Canada was an early mover in quantum, many other countries are investing heavily to help build their cooperative ecosystems and become quantum frontrunners. Participants noted that the budget for the NQS is not large enough to compete with other countries and that Canada may be overtaken in quantum without significantly greater investment. Quantum will be a longer-term play and may require more than a scale-up of existing programs.

A number of funding approaches and vehicles were suggested, including:

- a quantum stream in the SIF;
- a program modelled on the U.S. DARPA (Defense Advanced Research Projects Agency);
- creation of a quantum category in ISED's Industrial and Technological Benefits policy, which specifies that a certain portion of contracted defence spending occur in Canada;
- expansion of Business Development Bank of Canada's Deep Tech Venture Fund and the federal Scientific Research and Experimental Development tax credit;
- founder fellowships that allow academics to focus on building companies;
- consortia focused on specific goals and/or areas of sectoral growth; and
- a national program to de-risk the adoption of quantum.

Roundtable participants and online survey feedback indicated a lack of awareness among industry and the broader public about quantum and its capabilities. It was suggested that Canada:

- **develop a communications strategy to leverage its positive brand** as a trusted ally;
- showcase quantum capabilities to generate awareness, opportunities and adoption; and
- start a discussion around security and ethics.

Better promotion, perhaps through an educational campaign, could profile quantum use cases and the value of quantum technologies, increase enthusiasm for quantum, encourage diversification of the quantum workforce and attract others to join Canada's efforts.

Building on awareness, **there is a need for clients and users to be involved early to help guide the development of quantum applications and advance adoption**. The quantum sector should identify synergistic opportunities where quantum can be coupled with other areas of Canadian strength, such as photonics, microelectronics and radio frequency expertise. Online input suggested that Canada follow the model that made it competitive in the semiconductor, photonics and information and communication technology (ICT) industries.

Bringing together several Canadian companies and investors to merge domestic efforts under a larger anchor fund would help to create a critical mass of expertise and resources to better compete internationally. **Focused industry-academic collaborations in areas of Canadian leadership**, such as mining and quantum sensing, could help to draw and retain talent, spur application development and attract external partners.

We need to think internationally from the start to facilitate exports and commercialization overseas, given the relatively small size of the Canadian market, a lag in the digitization of some sectors and a shortage of well-informed buyers. In addition, the largest investors and early adopters of new technologies tend to be in other countries.

Participants noted that creating new, or leveraging existing, international networks and markets and establishing an international network of alliances will help to broaden opportunities for Canadian companies. Partnerships with those who can provide access to existing quantum capacity will be particularly valuable. Participants proposed candidates for strategic international partnerships, including big commercial players (e.g. Microsoft, IBM, Google, Amazon) and jurisdictions (e.g. the European Union, Germany, France, U.K., U.S., Australia), as well as defence and economic partners (e.g. Five Eyes, NATO and G7 nations).

Along with pursuing international agreements with partners, government could support the setting of international standards and regulations, which afford clarity that can reassure new technology adopters and enable market opportunities for Canadian companies. A note of caution was raised regarding over-regulation, which could impose limitations on the nascent quantum sector.

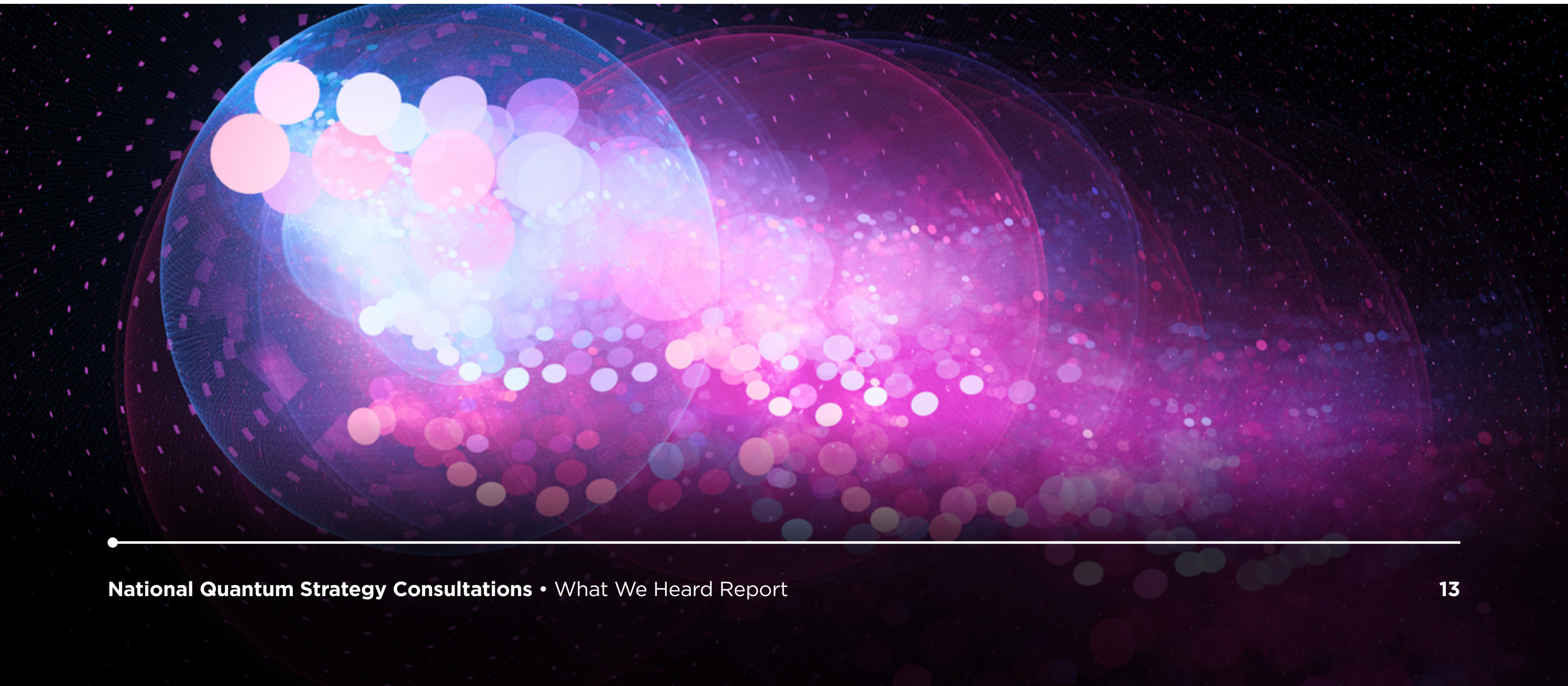
Diplomatic outreach through scientific attachés and trade commissioners could be enhanced, particularly for small companies with less commercial experience. These representatives can generate leading-edge scientific and market intelligence, and provide recruitment services. The "Quantum 101" training that Quebec offers could be used as a model for building expertise.

Findings specific to commercialization identified:

- potential application areas for quantum technologies;
- approaches to advancing adoption;
- the need to develop a quantum ecosystem; and
- solutions to scaling up quantum in Canada.

Many **potential application areas** that will be accelerated by quantum were discussed in the roundtables and identified in the online survey, including:

- **Communications:** Networks; quantum key distribution; quantum internet – all with near-term opportunities and Canadian expertise.
- **Sensors and transducers:** There are near-term, readily available opportunities in this area.
- **Computing:** Hardware, software, middleware, algorithms, information processing, cryptography; artificial intelligence and machine learning; and various applications, including finance (e.g. portfolio optimization), computational chemistry (e.g. advanced modelling of pharmaceuticals), the environment (e.g. simulation of climate-change solutions), transportation (e.g. logistics) and other opportunities for optimization.
- **Hybrid computing:** Roundtable and survey participants expressed the need to bridge classical and quantum computing with hybrid technology while society transitions toward quantum computing.



It was also noted that the greatest potential for quantum technologies may be for uses we have yet to discover.

Areas where Canada has particular strength include:

- quantum cryptography (as noted above);
- stack co-design and code optimization, error correction and fault tolerance;
- quantum optics (national expertise in photonics and optics); and
- quantum repeaters (expertise in satellites, including new low earth orbit or LEO satellites, and photonics).

These applications have very different timelines for commercialization. Some, such as new materials and drug discovery, may be only three or four years away, while applications in communications and computing may take five to fifteen years to develop. Other fields can impact the development of quantum technologies.

A general approach to advancing quantum technologies was suggested. It involves:

- first understanding the technologies, their technology readiness levels and what this means for the sector in terms of jobs;
- developing a plan to benefit from each technology and mitigate risks, such as planning, testing, vendor engagement, prototyping and standards development; and
- implementing the plan.

Government can have an important role in **advancing the adoption of quantum** through multiple approaches, including:

- mandates and adoption incentives, similar to tax incentives for electric vehicles, as well as tax incentives for companies to invest and locate in Canada;
- specific incentives for target industries supported by private-public partnership models;
- promotion of quantum to large Canadian investors and education in quantum technologies' commercialization;
- a joint federal-provincial approach to commercialization, including support for practical tools, such as a common platform to test and bridge commercial gaps identified by industry (e.g. Canada's Centre of Excellence in Next Generation Networks, or CENGN), as well as improved access to public data sets to find solutions to existing problems and fuel innovation;
- programs and policy levers like Innovative Solutions Canada;
- national laboratory facilities and expertise to solve fundamental science problems and bridge efforts between academia and industry;
- early-adoption of technology into operations to build understanding;
- export supports; and
- more regular procurement that follows contribution agreements and support like NRC-IRAP.

Government procurement was seen as an important tool, particularly as there are no major companies in Canada currently filling the role of first buyer. It was noted that better information sharing and more flexible procurement processes, especially involving the Department of National Defence (DND), would support smaller companies and innovation.

Participants proposed a three-pronged approach to increase adoption of quantum technologies domestically:

- education to raise awareness and explain quantum technology;
- experimentation to encourage corporate Canada to explore and test solutions; and
- pilot projects to build quantum use cases and promote uptake.

As commercial quantum products and services become available, firms will have to recognize their value. Companies tend to be technology neutral and will support whatever tools provide solutions and improve their bottom line, but we need to be clear about any risks involved, including the risk of inaction and the resources required for adoption.

By approaching companies to better understand their problems, technology developers can better target their development efforts and build quantum use cases. Broadening the discussion to include people with different perspectives can generate new insights. Banking and finance are positioned to be early users and are well-financed. A similar message was offered in the survey: with the finance and defence sectors driving innovation, it could be opportune for government to connect with leading businesses, not just start-ups, in these sectors.

Canada needs to **develop a quantum ecosystem** that includes firms ranging from small and medium-sized enterprises to multinationals, supply chain partners from all parts of the technology lifecycle, not-for-profits and academic institutions to make quantum a sustainable, vibrant and robust sector.

Participants indicated that existing clusters and centres of excellence should continue to be supported, rather than spreading resources thinly throughout the country. Incubators and accelerators, as well as programs like the NRC's Internet of Things: Quantum Sensors Challenge program and DND/DRDC's Innovation for Defence Excellence and Security program were highlighted. A central point of contact within government will be invaluable as an umbrella for coordination and roadmapping.

From translating research to commercialization, in order to advance adoption at home and compete abroad, Canada faces a number of challenges to **scaling up quantum**. Potential solutions include:

- building a strong entrepreneurial culture;
- connecting developers with potential users (receptor industries) to generate quantum use cases and match solutions; for example, start-up companies should work closely with the larger private sector players that drive the economy (e.g. banking, telecommunications);
- creating a quantum technology transfer centre;
- promoting initiatives that support start-ups, like the Creative Destruction Lab;
- expanding strong funding programs, such as the NRC's Internet of Things: Quantum Sensors Challenge program and Sustainable Development Technology Canada; and
- using government procurement to de-risk, demonstrate and develop user confidence in quantum technologies.

Roundtable participants and online respondents spoke to specific scale-up issues of Canada's small technology supply chain and the need to establish some critical infrastructure. It was suggested that the NQS address "manufacturability" that will be needed to develop a quantum manufacturing pipeline. Specifically, it was recommended that Canada should address all the links in the value chain: research, prototyping, packaging, testing and production capacity for modest to large volumes, when required.

Talent pillar findings

THE IMPORTANCE OF RECRUITING, retaining and developing quantum talent featured prominently in all of the roundtable discussions and online survey results, as it relates to all of the other NQS pillars and themes. Simply put, as global competition increases, Canada must effectively attract and supply academia and industry with quantum-proficient talent to avoid a shortage of skilled labour and remain competitive.

The **overarching findings** pertinent to talent included:

- the timing and pace of efforts to meet talent needs;
- funding uncertainties that impact Canada's ability to retrain talent;
- the role of industry-academic collaboration in fostering talent retention;
- the need for communications and a branding strategy to attract talent to Canada; and
- the use of other levers to strengthen our position in the international competition for talent.

There was consensus that **ramping up the talent pipeline must happen immediately and rapidly**. It will take time, and many other countries have already begun to act.

Developing, attracting and retaining talent is critical. Quantum remains a nascent field, and HQP are key to driving its development. Canada must not only continue to develop and attract new talent, but also hold on to its existing talent. As mentioned in the Commercialization section, companies require quantum-literate staff who can translate concepts and research into useful ideas. Skill sets, such as systems analysis, engineering and business expertise, will become important as quantum moves toward commercialization. The presence of quantum-knowledgeable employees in a wide variety of companies and industries will support the acceptance and adoption of new technologies.

In academia, many HQP are lost to other countries because there is not enough funding for fellowships and postdoctoral and research scientists. It was suggested that Canadian universities should facilitate the transition from postdoctoral to academic postings, so that candidates have opportunities at home and are not hired away by other countries. It was noted that to provide stability to grad students, secure funding of at least five years is needed.

Effective talent funding programs were mentioned, such as the NSERC's CREATE program, which have been successful in developing next-generation talent.

The Alberta Technical University of Munich School program between the University of Alberta and Germany also helps to identify and fund HQP.

On the issue of **funding**, for HQP engaged in commercial ventures, concerns were expressed that many people trained in quantum leave Canada to create start-ups where venture capital is easier to obtain and the environment is more business-friendly.

Increased industry-academic collaborations are needed to pull research talent into innovation ecosystems and industry. The Southern Ontario Smart Computing Innovation Platform, NSERC and Mitacs support for transitioning HQP to industry were cited, although the current level of commercialization in Canada limits receptor capacity.

Support for cutting-edge research also attracts and retains top talent and creates an environment in which a vibrant start-up community can thrive. It was noted, however, that growing start-ups into big companies, rather than aiming to be bought out, will require a culture shift.

While most people can now work from anywhere, place remains important. The NQS should **leverage Canada's brand** by highlighting its social, cultural and economic advantages. We have a compelling story, but we need to tell it better to those pursuing their studies, research and commercialization. Widely publicizing the NQS will raise awareness and signal support for the sector, which could help to attract and retain talent. A Canadian emphasis on the responsible and ethical use of quantum for the greater good could be an attractive brand differentiator. (See more on societal and ethical considerations in the Other findings section.)

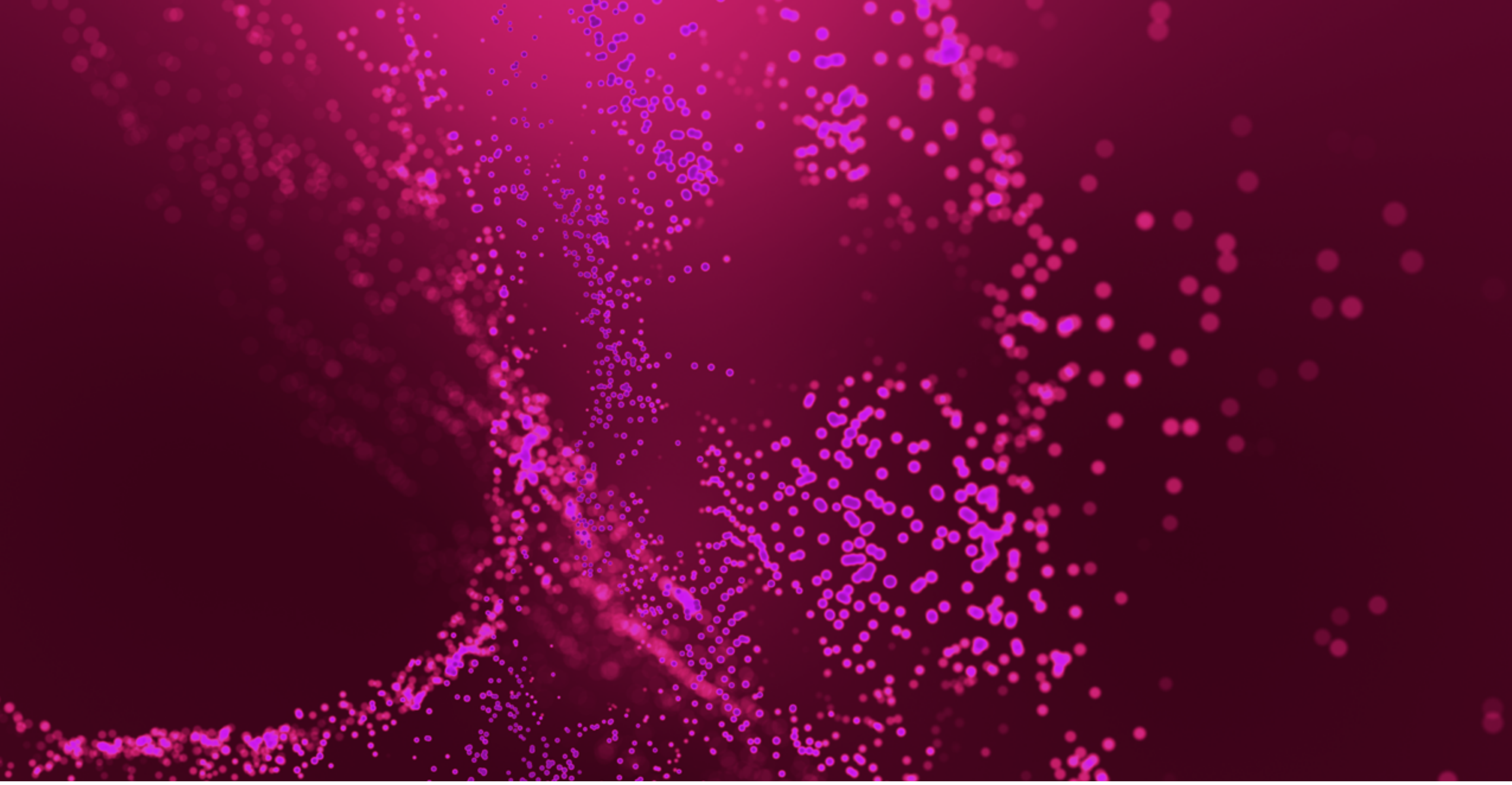
There was consensus that Canada should be concerned that other countries are investing heavily in quantum, as we are in **international competition to attract and retain talent**. Canadian society can be very attractive to foreign talent. However, Canada can do a better job in using international networks to our advantage and in developing cooperation agreements with other countries. On the academic front, international joint PhD programs and other mobility programs can help bring international students to Canada and enable Canadian students to study abroad. Mitacs could play a bigger role as a talent bridge between global centres of excellence, as well as between research and industry. In addition, the NQS could support programs that enable HQP sharing and training between universities and international quantum technology companies.

To enable Canada's talent efforts, participants suggested the need to support immigration and fast-track residency, while motivating foreign companies to set up shop in Canada. There should be a consistent approach across all levels of government and government agencies with respect to global talent and knowledge mobilization, including enhancing visa flexibility for visiting research and innovation talent, and lifting provincial government limits on the number of international graduate students recruited in a given year.

In addition to the overarching findings, **talent-specific findings** emerged, including the need to:

- address education and training;
- enhance equity, diversity and inclusion;
- overcome skills challenges; and
- improve knowledge translation and mobilization.

Education and training are at the core of talent. Leveraging efforts to improve STEM education in Canada will deepen and broaden the quantum talent pool – from undergraduate to post-graduate to professional – and prepare the population for the emerging economy. To this end, understanding user problems and applications for quantum must begin now to help target talent needs and develop the supply that will be required as technical capacities come online. We should start by looking at needs for the next five to 10 years. It was also suggested that Canada offer graduate students entrepreneurial training so they can start their own companies. It was also noted that the college and CEGEP sector is an important player in developing and supplying the talent pool.



While Canada needs to fill workforce gaps in expertise and train talent across supply chains, each quantum technology and application area will have specific needs and challenges. It was suggested that government can play a role in assessing these gaps. Participants offered quantum computing as an example. It will need talent in hardware and, subsequently, software. A strong quantum computing hardware industry may require talent in cryogenics, microwave engineering, computation and error correction. Later, application engineers will be a priority.

On-the-job training, retraining and upskilling will be important to develop the workforce. It was suggested that many general engineers could shift into quantum with specific upskilling and that Canada could capitalize on expertise in fibreoptics and wireless hardware engineering, which can be adapted to quantum computing hardware. Post-secondary certificate and continuing education programs that offer hands-on opportunities will be needed. However, some participants felt that upskilling is not realistic, especially for positions requiring in-depth expertise. To incentivize HQP retraining in quantum, Canada should consider increasing PhD stipends.

Further, companies could play a mentoring role with candidates who may not be ready to take on quantum-related jobs. Companies can also encourage quantum career-seekers by helping them understand how best to expand their skillsets.

Ideas put forward to **enhance equity, diversity and inclusion** include:

- creating a more inclusive environment to expand the talent pool;
- offering introductory courses in quantum, especially to students in other STEM fields and undergraduate programs, not just MSc and PhD candidates;
- targeting diverse colleges, CEGEPs and universities in Canada and abroad;
- drawing staff from other sectors;
- increasing diverse representation on panels and in promotional engagement;
- following the approach outlined in the Government of Canada's Dimensions Charter;
- replicating programs, such as the Creative Destruction Lab's Apprenticeship program or IBM's Polytechnic program with Six Nations; and
- facilitating the immigration of qualified candidates.

A wider range of students is expected as quantum technologies become more broadly adopted.

There is huge competition for the relatively few female candidates in quantum technologies, but this has not necessarily translated into more women entering relevant programs of study. More Indigenous students are entering STEM programs, but they sometimes face dilemmas in leaving their communities and culture, particularly if they have to go abroad.

To further attract diverse candidates, we should look at human-centric strategies. To this end, online comments included offering better parental leave and childcare, removing labour market impact assessments for PhDs, issuing special visas for experts in emerging technologies and making it easier for foreign students to stay in Canada.

Skills challenges include sufficient access to talent with the right combination of sophisticated skills to help advance from research to commercialization. These needs include quantum-ready talent that can recognize the value and competitive advantage of adopting quantum technologies, translate research discoveries, create new quantum applications and integrate the technologies across various sectors of the economy.

There is a shortage of talent familiar with both quantum physics and engineering, and even fewer candidates with business training. Few are fully equipped to lead commercialization, start their own companies or market their inventions. It was proposed that academia could establish cross-disciplinary programs that bridge engineering, science, business and social sciences to develop graduates with an understanding of the use of quantum technologies, their implications and how intellectual property can be leveraged.

Other specific skill deficits identified by participants included cybersecurity, engineering skills across the full stack of quantum computing-enabling technologies, project management, coding best practices, critical thinking, customer engagement and interview skills. Some suggested that quantum engineering should be identified as a priority talent stream for immigration. Priority designations need to evolve to allow Canada to access talent.

There was consensus that a lack of access to quantum platforms can limit hands-on practical training opportunities. One solution proposed is to look to models that offer quantum platform access to students and companies. (See ensure open, equitable access to quantum technologies in the Research section, above.)

Along with creating opportunities to retain talent (covered above in the context of international competition), participants recognized the need to **improve knowledge translation/mobilization** between universities and industry. Trainees need work experience to learn how to function in business settings and team environments. Research internships, such as those delivered through Mitacs, were recommended to help fill this need and bring graduate students into industry. Universities should likewise seek to bring more industry experience onto their faculty rosters and create knowledge translation opportunities for industry to learn more about research advances.

Security findings

CANADA NEEDS TO KEEP PACE WITH technological disruptions and emerging risks to protect privacy, critical information and information and communication technology (ICT) systems. Canada has strong expertise in technologies that enhance cybersecurity against these risks and we can be a leader in the advancement of quantum readiness and agility, both nationally and internationally. Consistent with the **overarching findings**, some of the responses suggested to meet this challenge and maximize this opportunity included:

- acting early;
- addressing our talent gap;
- working with limited funding;
- raising awareness of quantum security;
- engaging with owners of sensitive assets; and
- collaborating strategically (e.g. in the international arena).

Participants stressed that quantum computing represents a significant risk to the cybersecurity of existing ICT systems through its ability to break traditional cryptography. As today's encrypted data could be decrypted in the future once quantum computers become available, **now is the time to act**. Consequently, Canada should respond proactively, placing a high priority on the timely development and adoption of quantum-resistant cryptography. Some participants suggested the NQS should address the lack of urgency associated with quantum, likely because some stakeholders see it as a distant development.

Existing critical infrastructure needs to be protected in order to be made "quantum-secure" or "quantum-safe," meaning resistant to cyber-attacks on their cryptography by adversaries that have quantum computers. Major new projects that are planned or underway need to address the risks posed by quantum computing. Planning now to build in quantum-safe features is preferable to trying to retrofit systems later. In many cases, existing technology may need to be replaced rather than migrated. The interoperability of old and new systems will be a major issue, as transitioning to new cryptographic systems may take years.

Canada needs to invest quickly in a parallel infrastructure for secure communications using quantum technologies, including critical space-based infrastructure, such as new satellites that could enable quantum key distribution (QKD) across vast geographies like those in Canada. Other countries have already invested heavily in quantum technology in space (e.g. China launched the world's first quantum satellite for QKD in 2016).

Those who own sensitive information and manage sensitive assets need to be engaged. Many companies, institutions and researchers are unaware of the nature of the quantum computing security risk and how to prepare to make data and information systems quantum-safe. It was pointed out that we need to look beyond near-term quantum cryptography risks. As quantum hardware rapidly evolves, we will need to monitor, identify and share information on new vulnerabilities as they arise. De-identification/anonymization and financial technology could be attractive targets.

To have the capacity to address quantum computing risks, **Canada must fill its significant talent gap**. Lead time is needed to develop the appropriate educational programming, so efforts should begin without delay. Since much of the required talent will not need to be HQP, it was suggested that college/CEGEP-based cybersecurity programs, incentivized with federal funding, could contribute to the talent-base.

When other countries hire away Canadian quantum talent, they may obtain a window into our capabilities and weaknesses. The NQS should address how to retain quantum talent in Canada.

Participants noted that **the $360 million allocated over seven years to the NQS is insufficient**. Industry will not invest in quantum-secure initiatives until the appropriate solutions are clear. Some participants also indicated that the investment/venture capital sector in Canada tends to be highly risk-averse. Hence, the federal government will need to play a leading role to drive quantum in general and encourage industry to move on the quantum security issue more quickly through mandates, incentives and funding.

Participants suggested that government should use its influence to **better promote Canada's quantum leadership and raise awareness of quantum security issues**, including both opportunities and challenges. We must foster a sense of urgency in responding to these issues.

While **collaboration will be needed** across the intelligence spectrum, as well as among experts and allies on international standards and possibly on other aspects of security, participants noted that federal government funding for collaboration between academia and business requires a trustworthy private sector collaborator. A collaborator found to be owned or controlled by another party deemed a security risk, even if they are not directly part of the collaboration, could place the partnership in jeopardy.

The landscape for quantum security is vast and of global interest. Partnerships with other countries can pose security risks, but they can also offer benefits. While we have some tools to enable us to discern the risks associated with international partnerships, some participants believed that collaborating through open access science and computer code provides broad transparency and a level playing field that can break down political barriers and provide protection against malicious software. Canada will also need to align with standards and frameworks for post-quantum cryptography. (See more on standards in the Other findings section.)

It was noted that no one country will be able to lead quantum in every aspect. Canada's contribution of the Canadarm to NASA's Space Shuttle program was cited as a model that could be considered to advance the development of quantum technologies. While significant international coordination would be required, focusing on a particular contribution could be beneficial to both Canada and the larger global effort.

In addition to the general findings, **specific security findings** included:

- laying the groundwork for quantum security;
- using government as an adopter;
- pursuing commercial opportunities; and
- ensuring the security of supply chains.

Laying the groundwork for quantum security involves prototyping hybrid/quantum-resistant cryptography systems, which should begin as soon as possible, followed by transitioning to post-quantum cryptography. The concept of crypto-agility (for transitioning from legacy to quantum-secure systems) should be built into NQS security considerations and into government IT systems and planning.

It was suggested that the availability of a testing platform for Canadian businesses lacking quantum experience or expertise would help them experiment with product deployment and realize the implications of quantum computing on cybersecurity.

Government should take the lead by becoming an early adopter of quantum, including security solutions. This will help to drive investment and innovation, provide testbeds, facilitate interoperability and foster commercial adoption. Government could also use its procurement, funding and regulatory powers to ensure that providers offer quantum-secure products and services. Regulation could be made progressive over time as quantum ramps up. It was suggested that the Department of National Defence could make a commitment to procure quantum technology from Canadian suppliers, who could work with the department to better identify its needs.

Since cryptography solutions are still being developed, Canadian innovation and investment have the potential to be on the leading edge of quantum security and make a global commercial impact. There will be significant **commercial opportunities** in transitioning organizations to quantum-secure solutions. Financial technology is expected to be among the early adopters of these solutions.

Quantum sensors offer an opportunity to provide a back-up to all types of existing sensors, including navigational systems, and there is potential for the data derived from such uses to be combined in new and unique ways.

QKD represents a near-term opportunity that can be employed as a stand-alone technology for niche applications or targeted uses. These applications can be viable on their own, regardless of whether other quantum technologies advance.

Dependency on foreign knowledge, technology and supply chains can pose security risks. These risks are compounded by the potential for quantum technologies to have dual-uses (both civilian and military), the complexity of modern supply chains, and the difficulty of building security into the design of emerging products.

Many of the supply chains for quantum technologies are outside of Canada, limiting our ability to make them secure. Some participants felt that over-reliance on other countries as suppliers puts us at risk, as did our lack of domestic capacity to manufacture personal protective equipment when COVID-19 hit.

Other findings

SOCIETAL AND ETHICAL CONSIDERATIONS

It was suggested that, as with artificial intelligence, Canada establish an ethical framework from the start and make a strategic commitment to the responsible and ethical use of quantum technologies for the benefit of humanity. Such an approach would provide Canada with a critical differentiator to attract talent and compete on the international stage with better resourced nations. This is an area in which Canada is well-positioned to be a leader.

Business and social science students should be trained in quantum-related issues and build competencies in a holistic way. This could help to diversify the workforce, increase quantum acceptance and contribute to Canada's unique quantum niche. The Social Sciences and Humanities Research Council of Canada could fund studies on the societal and ethical considerations of quantum technologies.

ADVISORY COUNCIL

Participants suggested that Canada should establish an advisory body akin to the U.S. National Quantum Initiative Advisory Committee, which would include academic, industry and government representatives. The European Union also has a quantum advisory committee.

Participants suggested that a Canadian body should have a well-defined purpose and function, a means to ensure impartial input and a way to ensure a diversity of perspectives. Groups to be represented could include industry (large and small), academia (early career and experienced), finance/investment, technology receptors and governments (federal and provincial). Both quantum advocates and those who are more cautious should be at the table, as should non-experts who would ask fundamental questions. Involving people with strong experience from other countries and a global view of the field would be helpful. The Canadian Forum for Digital Infrastructure Resilience (CFDIR) and Photonics U.K. were offered as models.

The Simulation Interoperability Standards Organization was offered as a model to create quantum computing product development groups and grow international expert communities. Online advice included forming separate advisory groups for distinct functions to avoid conflated roles.

INTELLECTUAL PROPERTY

Knowledge generated from research can hold significant future commercial value. Key to Canada's success is ensuring that IP generated by Canadian post-secondary institutions, researchers and companies can be protected and leveraged for future innovation. Concerns over retaining IP rights, maintaining firm equity while seeking investment and the risk of mergers and acquisitions can arise as companies look to scale-up to better compete.

Participants noted that IP ownership can be difficult to navigate. As the quantum field is populated by HQP who are closely associated with a university or recently graduated, many are bound by the IP ownership rules established through their institutions.

The general view is that, if IP is derived from research funded by public dollars, benefits should accrue to Canada. In other words, we could tie public funding to the condition of keeping IP in Canada. Some participants also saw domestic manufacturing as a way to prevent IP theft. It will be important to strike the appropriate balance between being restrictive and open in the treatment of IP. It was noted that we must be careful not to create unintended barriers to development and commercialization. The need for IP to remain in Canada could be a barrier to international investment.

STANDARDS

Participation in international technology standard-setting activities, including those around quantum communication and metrology standards and protocols, can lead to opportunities for a country's technologies to be accepted as standards, resulting in benefits, such as export markets and economies of scale. While many nations are focusing considerable investments in R&D of quantum technologies, some are also stepping forward to drive an international standards agenda. Their interests do not always reflect Canadian principles, such as strong security, interoperability and net neutrality.

It was suggested that Canada needs to take a leading role in the development of international standards to build thought leadership, contribute its perspective (including on the ethical use of quantum) and influence the development of mutually advantageous standards. From a security perspective, it would be helpful to partner with standards bodies for cryptographic protocols, such as the U.S. National Institute of Standards and Technology (NIST) and the European Telecommunications Standards Institute. NIST is expected to release guidance for quantum-safe algorithms in the next three years. It was noted that the Quantum Readiness Working Group at CFDIR is developing guidelines for Canadian businesses, starting with financial services, and this work is aligned with NIST.

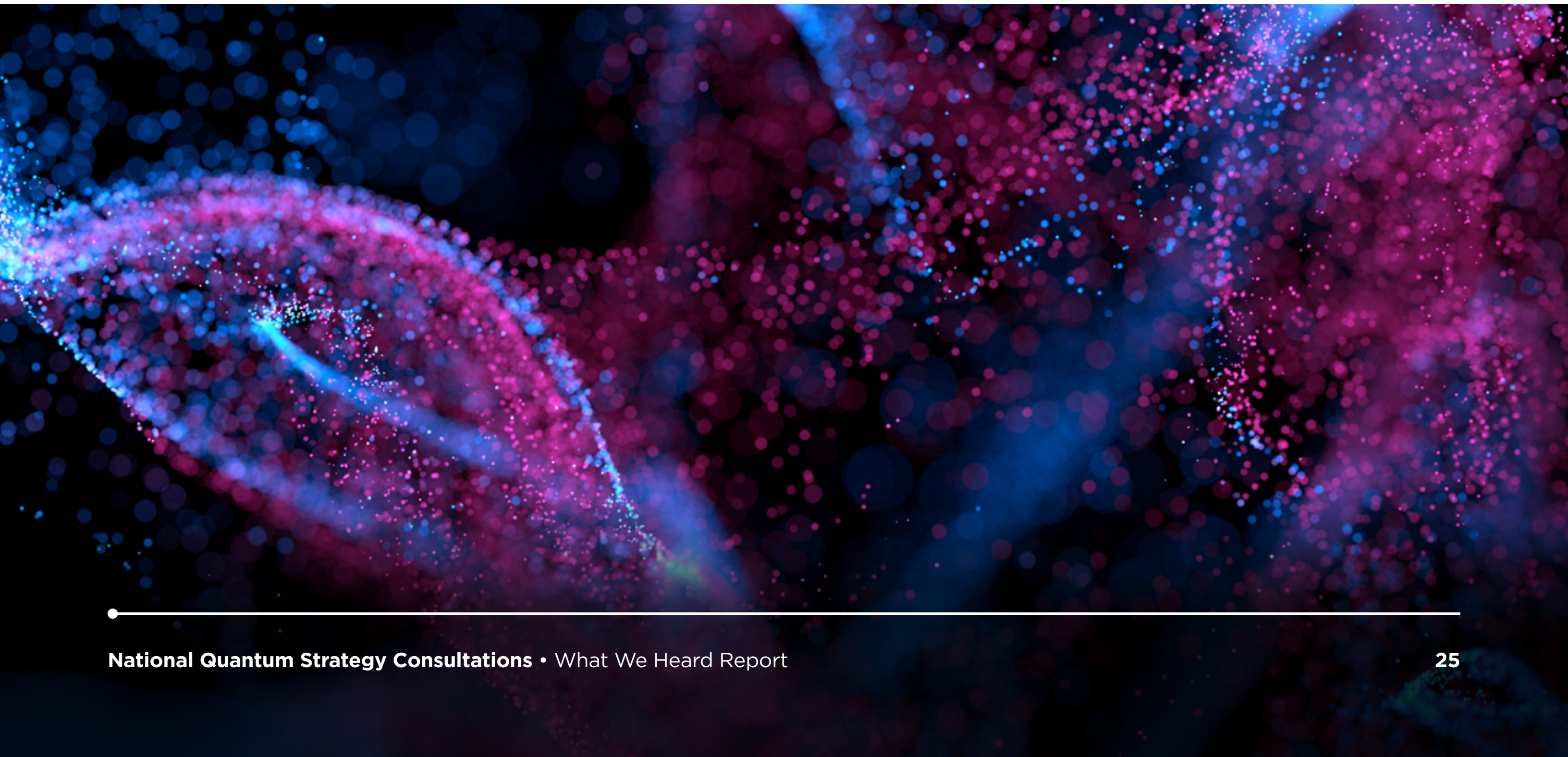
Models suggested for convening interested parties included the Standards Council of Canada; SAE International, formerly the Society of Automotive Engineers; and the British Standards Institution.

Conclusion and next steps

QUANTUM HAS BEEN IDENTIFIED AS AN emerging area that can fuel Canada's economy, long-term resilience and growth, especially as quantum technologies mature and more sectors harness their capabilities. Preparing Canada for, and maximizing the benefits of, quantum technologies will require ongoing collaboration spanning Canada's quantum community, with academia, industry and all orders of government working together for some time to come.

What we heard in summer 2021, through roundtables, survey responses and email input, complements earlier advice shared by a university-private sector quantum consortium in 2019, as well as insight provided to the Chief Science Advisor of Canada, Dr. Mona Nemer, who convened a group of domestic and international stakeholders in spring 2021.

Informed by these rich sources of input and guided by the goals set in Budget 2021, ISED's NQS Secretariat will continue working with members of the quantum community to advance the NQS.



Annex: consultation questions

1. Which applications and research areas offer the greatest potential for Canadian researchers and firms to strengthen their leadership to succeed globally? What stretch goals and priorities can be set for these applications in the next three years and beyond to make a roadmap for a leap forward?
2. How can academia, industry and government work better individually and collectively to accomplish national objectives in quantum technologies?
3. What are the key challenges and opportunities for academia and industry in the development, attraction and retention of talent?
4. What can be done to ensure that, as Canada's quantum sector grows, it is increasingly representative of our diversity?
5. What are the greatest opportunities and challenges in commercializing quantum innovations in the Canadian context? Do different quantum technologies (e.g. sensing and imaging, computing hardware, algorithms, communications and materials) require specific approaches?
6. How can the NQS help to ensure that, as quantum technologies and solutions come to fruition, they are adopted by Canadian businesses, academia, government and the public?
7. How can the NQS best address the societal, ethical, legal and policy considerations that may arise given quantum technologies' disruptive capability?
8. How can we leverage and mobilize Canada's research and business strengths to connect with international partners? How do we ensure we derive maximum benefit from these collaborations?
9. How should the NQS address emerging security risks and build on Canada's expertise to create commercialization opportunities?
10. What specific gaps, barriers and challenges hinder our efforts to solidify Canada as a global leader in quantum technologies?
11. What best practices have you seen in Canada and/or abroad that we should consider when forming an advisory body?
12. Are there any considerations that we have missed, questions we should ask or elements we should explore further?