National Defence / Défense nationale

CANADIAN ARMED FORCES

DEPARTMENT OF NATIONAL DEFENCE
AND CANADIAN ARMED FORCES

Quantum

S&T STRATEGY: PREPARING FOR TECHNOLOGICAL DISRUPTIONS IN THE FUTURE OPERATING ENVIRONMENT

Canada

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FOREWORD

Science and technology (S&T)

has always played a key role in meeting national defence and security needs with emerging technologies often enabling decisive tactical advantages. The pace of change and emergence of a new class of quantum technologies has markedly increased over the last several years and has the potential to influence and disrupt the defence and security landscape.

As these technologies evolve, so too must the Department of National Defence (DND) and the Canadian Armed Forces (CAF). For these reasons, I am proud to present the DND/CAF *Quantum S&T Strategy: Preparing for technological disruptions in the future operating environment.* This strategy will leverage important work the department has already accomplished in the field of quantum S&T and align future work to meet the needs of the DND/CAF.

The *Quantum S&T Strategy* will allow DND/CAF to take a strategic approach to this emerging field, centered on three organizing pillars. First, the strategy will help DND/CAF transition quantum technologies out of the lab and into deployable defence capabilities, focusing first and foremost on the technologies with the most immediate and most significant impact on the CAF. Second, recognizing the breadth and complexity of quantum technologies, the strategy encourages the building and leveraging of strong partnerships across the Government of Canada, academic institutions, Canadian industry, and with international partners, to ensure that DND/CAF can benefit from a comprehensive approach to quantum research. Thirdly, the strategy will bring coherence to quantum S&T investments within the Defence Team, building internal research capacity and human capital ensuring that we have what it takes to compete in the 21st century and beyond.

This strategy will ensure that the Defence Team is well prepared to face the challenges and opportunities of emerging quantum technologies while supporting the academic and industrial quantum ecosystem that is already thriving here in Canada.

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ADM(DRDC)

BACKGROUND

The Department of National Defence (DND) and Canadian Armed Forces (CAF) must be

prepared

for a future defence and security environment that includes and protects against advanced capabilities based on disruptive quantum technologies. The purpose of this strategy is to ensure that such technologies are available and suited for early adoption by DND/CAF.

The Canadian government has invested heavily in quantum science and technology (S&T) over the last two decades, with Canada now ranking amongst the world leaders in the generation of knowledge in the field. As a result, DND/CAF is in a position to access and influence a deep pool of existing talent without the need to build the extensive, specialized infrastructure required to do the foundational research, or the specialized engineering core to transition quantum technologies into practice. Instead, DND/CAF can focus on key areas of quantum S&T that leverage Canadian expertise and strengths showing the most promise for delivering enhanced defence and security capabilities. This strategy will identify areas that require focused investments and outline how DND/CAF will build appropriate expertise and leverage partnerships in order to accelerate the development of quantum technologies for defence and security needs.

While Canada has strength in quantum S&T, targeted investment by other nations is eroding Canada's leadership position. Nationally, there are consequences to falling behind, as quantum technologies are expected to be a growth engine in the future world economy. The risk to DND/CAF is that other nations will be able to field a range of quantum-based technologies that give them capabilities that Canada is unable to either match or counter. This risk is especially acute given that potential adversaries are investing heavily in new capabilities across domains to challenge the Western military advantage.

Quantum

mechanics has been around for more than a century and is recognized as the most significant and successful theory in modern physics. Nevertheless, quantum remained in obscurity for many decades primarily because of its counter-intuitive foundational principles, the complexity in performing experiments, and the difficulty in communicating its properties using non-technical jargon. It has been said that the two most important and perplexing properties of quantum mechanics, superposition and entanglement [See Figure 1], can only be precisely and accurately described using the language of mathematics. These two properties, however, underpin technologies that proved to be disruptive in the past and are anticipated to be disruptive in the future.

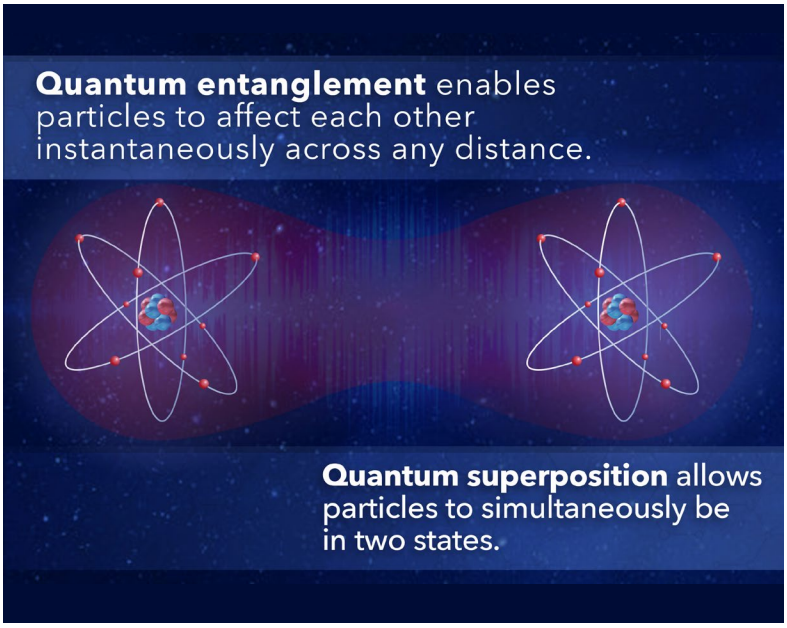


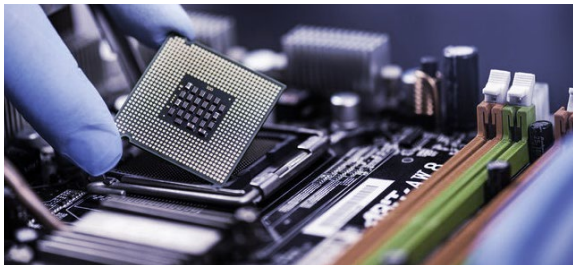
Figure 1: Quantum entanglement and quantum superposition definitions

Quantum 1.0

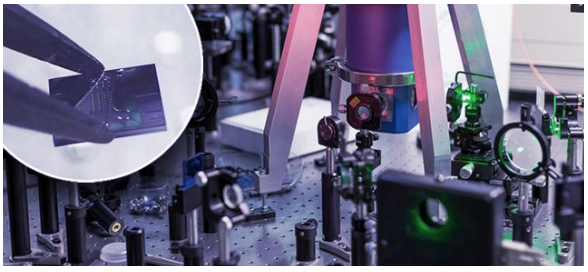
The first generation of quantum devices revolutionized defence and security capabilities and transformed society. The two most salient examples of technologies that are fundamentally reliant on the effects of quantum mechanics, technologies now known as Quantum 1.0,[1] are the transistor and the laser, which form the foundation of our modern digital age and are key enablers of a range of technologies [See Box 1].

In the past decade quantum has become an enthusiastically discussed topic in popular science and, thanks primarily to the public attention surrounding quantum computing, has entered the vernacular. The first generation of quantum technologies have continued their rapid development and have, in turn, became key enablers for the engineering advances required to bring about the next quantum revolution.

BOX 1

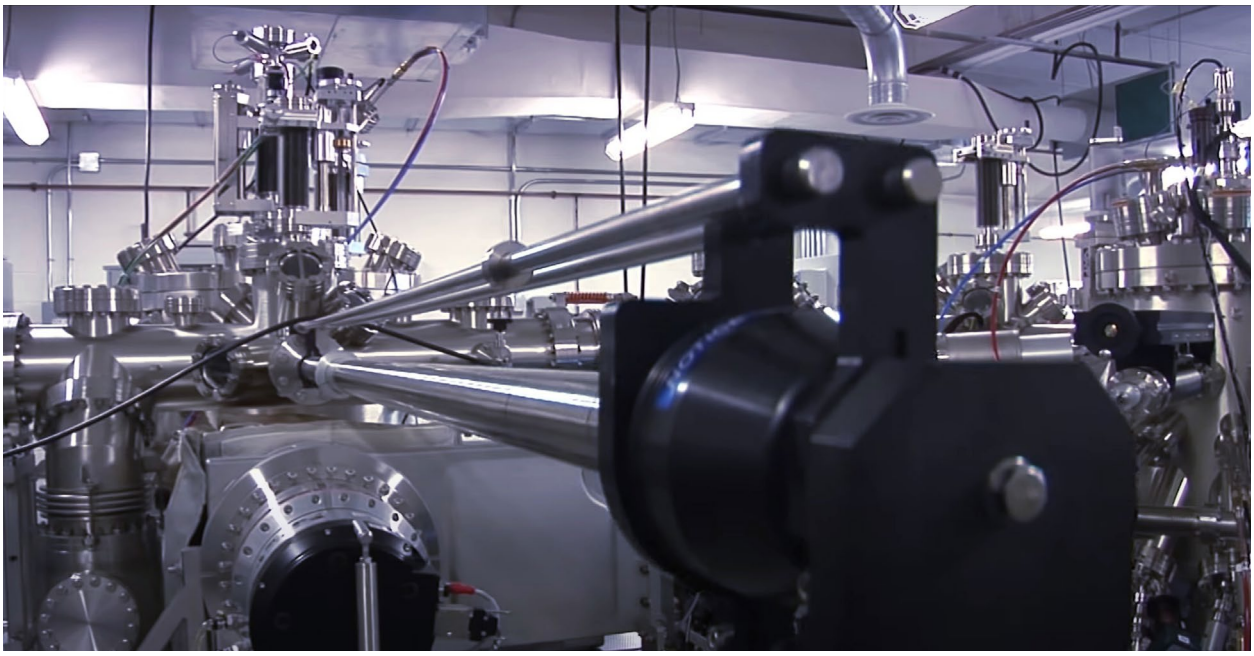


The first quantum revolution gave us new rules that govern reality. A transformative example of such a harnessed physical description led to lasers, circuit boards, and silicon-based electronics.



The second quantum revolution allowed for the precise control and manipulation of these quantum properties of light and matter which are entering the engineering stage of applications.

1 J. P. Dowling and G. J. Milburn, *Quantum Technology: The Second Quantum Revolution*, 2002. Ultimately, all of nature relies on the fundamentals of quantum mechanics, but if a technology can be sufficiently described using the laws of classical (pre-quantum) physics it is not considered part of Quantum 1.0.



Credit: University of Waterloo

Quantum 2.0

A new generation of technologies, Quantum 2.0, has emerged over the last fifteen years due to more controlled isolation and manipulation of delicate quantum systems. Quantum 2.0 is defined as "a class of devices that actively create, manipulate and read out quantum states of matter, often using the quantum effects of superposition and entanglement" [1]. Quantum 2.0 systems can include materials constructed with atomic precision, the creation and stabilization of subtle states of matter using highly precise lasers, or the encoding of information onto atoms and single photons of light. These systems are unique in their ability to leverage and control previously inaccessible properties of nature, allowing for stunning new capabilities such as quantum computers that can quickly solve certain types of problems that a classical computer cannot.

Currently, most quantum proof-of-principle and early-stage engineering applications reside in university laboratories and the National Research Council Canada (NRC), requiring expensive infrastructure, specialised equipment, teams of experts, and large footprints to operate. However, in some technology areas where defence departments have begun investing, the transition of Quantum 2.0 technologies out of the laboratories and towards prototypes has begun.

Quantum for Defence and Security

Quantum technologies will deliver significant capability enhancement in areas of known defence and security interest. The areas that will likely see the greatest disruption across the quantum technological landscape are sensing [including Positioning, Navigation and Timing (PNT)], communications, computing, and the development of new materials. At the same time, the ability of adversaries to exploit quantum technologies for their aims will affect the tactics, techniques, and procedures that the Defence Team must employ to achieve its mission.

Quantum sensing serves as a salient example of the breadth and utility of quantum applications that currently exist at low technology readiness levels and that are uniquely positioned to impact the defence and security landscape in the next five years. Quantum systems are easily perturbed and therefore ideally suited for core defence and security sensing applications. Traces of electric and magnetic fields, gravitational variations, vibrations, or motion are detectable by quantum systems at levels unachievable by classical systems. Transition of these technologies out of the lab will lead to capabilities such as:

- Gravimetric sensors that can detect tunnels or objects behind walls;
- Compact, wide-band electromagnetic sensors that outperform and replace multiple antenna systems;
- Stealth-defeating radar that is difficult to detect and jam;
- Precise and covert range-finding techniques that can see through smoke and around corners;
- Detection of trace levels of chemicals and radiation at sensitivities and distances not possible with existing techniques; and
- Compact inertial sensors and clocks that can maintain sufficient accuracy for Defence to complete its missions in Global Positioning System (GPS)-denied environments, including underwater and underground.

Some of these potential capabilities could provide solutions to new and emerging defence challenges, such as the need for greater surveillance over the vast Canadian Arctic and the aerospace and maritime approaches to Canada and North America. The wide potential application of quantum technologies means it may deliver surveillance capabilities across domains and as part of a layered "system of systems" to provide the CAF and North American Aerospace Defense (NORAD) with innovative all-domain awareness capabilities.

Quantum sensing is not alone in its applicability to defence and security. For example, quantum communications will bring capabilities such as covert communications, anti-spoofing, jamming resistance, and secure key distribution. Quantum computing promises the ability to solve certain types of problems that cannot be solved on a classical computer, such as optimization-based logistics and the breaking of most currently implemented cryptographic protocols. For all quantum technologies, the transition path out of the lab, into prototypes, and towards fieldable equipment remains a complex scientific and engineering problem. Presently, the ability to transition quantum technologies to higher technology readiness levels (TRLs) is an area of global competition which underscores the need to protect Canadian research and innovation in the field.

The defence and security applications of quantum technologies have been recognized by a number of other nations; the United States, United Kingdom, Germany, and China have already launched large-scale national quantum strategies that are coupled to their defence interests. China, in particular, has risen into the ranks of the world leaders in quantum S&T and has invested heavily in areas that promise to deliver new and enhanced military capabilities. Assuring and countering such capabilities is a concern unique to Defence.

The Canadian Quantum Landscape

Canadian foundational quantum research—fueled by early federal, provincial, and philanthropic investment—has positioned Canada as a leader on the international scale. Quantum science is a fixture in the national science and technology strategy, *Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation* (2014) [2] and quantum computing has been named one of the digital focus areas of the national innovation agenda, *Canada: A Nation of Innovators* (2016) [3]. Such academic quantum research excellence and expertise coupled with Canada's thriving technology entrepreneurship [4] point to a promising environment for leading edge quantum innovation.

Canada stands to gain much from its heritage in the development of quantum technologies. It is projected that by 2040 the up-and-coming quantum industry sector will be a strong contributor to the Canadian economy (between 1.7% and 3.4% Gross Domestic Product (GDP)) [4]. The sector's projected revenues are expected to match what the aerospace sector, Canada's most Research and Development (R&D) intensive industry, contributes to the national economy today. However, this rapid technology pace also points to labour shortages in quantum-trained, broadly-skilled personnel both in Canadian industry and government and also around the world [5].

The Department of National Defence will take a comprehensive approach to ensure that DND/CAF can

transition quantum technologies into military capabilities.

This will include anticipating and evaluating the military implications of quantum technologies, defining defence focus areas for quantum science, technology, and innovation, and establishing the conditions that accelerate the fielding of quantum-based technologies. Defence mission success will also depend on understanding and exploiting vulnerabilities introduced by quantum technologies, as well as safeguarding quantum investments by ensuring potential adversaries do not acquire the research, intellectual property (IP) or technologies funded by DND/CAF under the Strategy. To succeed, the strategy will be focused on three pillars to ensure that DND keeps abreast of the state-of-the art in quantum research development and is able to efficiently transition these technologies as they mature:

1. Transition quantum technologies into Defence capabilities;
2. Establish and sustain strong partnerships in quantum technologies; and
3. Bring coherence to quantum science, technology, and innovation investments across DND/CAF.

Successful implementation of this strategy is dependent on each of the key enabling activities discussed under each pillar.

Pillar 1:

Transition quantum technologies into Defence capabilities

The conditions under which DND/CAF operate define unique requirements and specifications for technologies to be fieldable. DND/CAF must ensure that quantum capabilities can operate reliably under all defence and security environmental conditions including denial, deception and subjection to countermeasures. Early engagement by DND/CAF to communicate defence-specific gaps and requirements to the quantum community will help define the path quantum S&T will follow in a build towards fieldable defence capabilities.

1.1 Focus on quantum sensing technologies

Sensing capabilities are a critical enabler of situational awareness and decision support. Canada has existing strength in quantum sensing S&T but the next generation of quantum-based sensors will not develop towards timely, operationally fieldable capabilities without DND/CAF influence and guidance. Resilient quantum sensors that are required to operate in harsh conditions and/or environments, at high speeds, and in a stealthy manner must start down that development path early. To ensure operational requirements are met, DND/CAF will engage with the Canadian quantum community, including those in government, in advancing quantum sensors towards integration into current DND research endeavors and eventual CAF application. The integration of quantum-based sensors into Defence capabilities will ensure that DND/CAF are not at a technological disadvantage when preparing for and conducting missions.

ACTION NO. 1:

Focus initial efforts on quantum sensing applications to take advantage of Canada's strong foundation in the field and establish world-leading expertise and capabilities in quantum sensing.

1.2 Develop assurance and countermeasures for quantum technologies

Quantum technologies that lack resilience cannot be fully integrated into DND/CAF operations; a robust understanding of quantum-enabled technology capabilities and vulnerabilities is required. DND must drive assurance-related S&T, including denial and deception as countermeasures for quantum technologies deployed against us. These aspects of technology are a defence and security-specific interest—one which will not be addressed without DND/CAF leadership and focus. Assessments of current quantum technology vulnerability and exploitation will feed into operational analysis and be addressed in DND integrated S&T program decisions.

ACTION NO. 2:

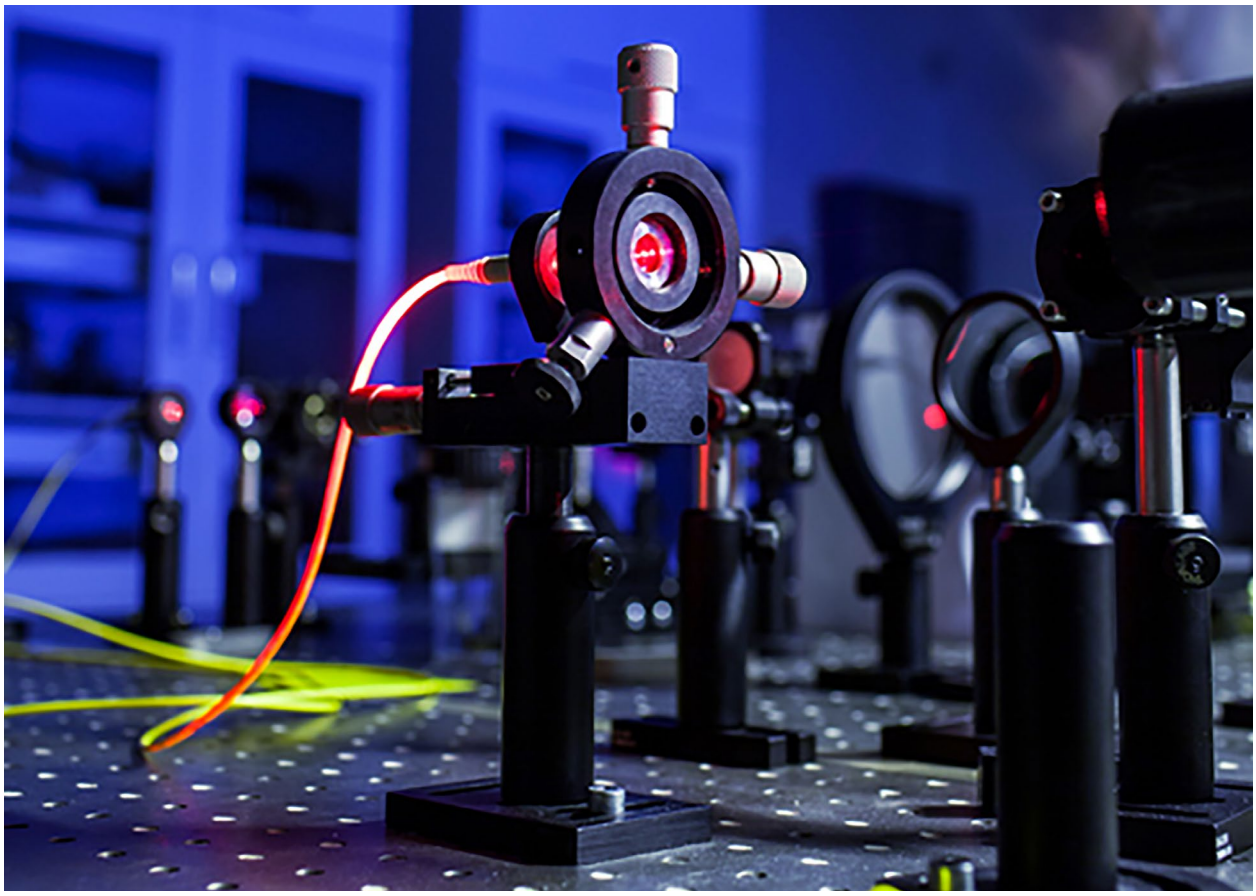
Conduct assessments of new threats and vulnerabilities that may be introduced by quantum technologies as they come online.

1.3 Accelerate the fielding of quantum capabilities

Quantum S&T is required across the whole spectrum, from fundamental research to applied engineering, in order to develop the next set of transformative technologies. DND is positioned to provide sandboxes and exploit S&T field trials to enable experimentation in realistic environments in order to increase the technology readiness levels of quantum technologies. Joint projects, experiments, and trials with international allies will be leveraged to achieve this aim, allowing DND/CAF to be prepared to exploit quantum technologies in a timely fashion.

ACTION NO. 3:

Place a strategic emphasis on enabling and incentivizing the transition of quantum technologies out of the laboratory into fieldable prototypes.



Pillar 2:

Building strong partnerships

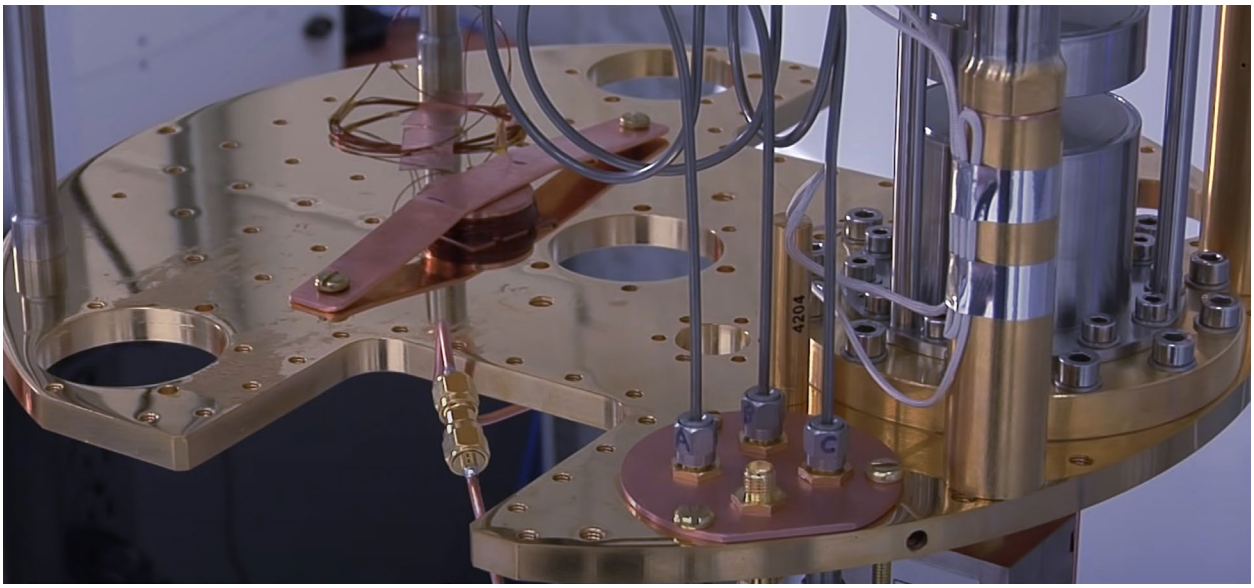
Partnerships are key to accelerating the adaptation of quantum technologies. The field is broad and deep, spanning a large range of highly technical skill sets. Different nations have different strengths, based on decades of past investment decisions. Additionally, a peculiarity of quantum technologies is that it is not uncommon for a promising approach to be overtaken unexpectedly by another, meaning it is advantageous to work on as many techniques as possible to "cover the bases". For quantum computing, large multinationals as well as small and medium-sized enterprises are investing heavily in different approaches, few of which may be the eventual winners. The risk of "betting on the wrong horse" is high, though the training of highly qualified personnel (HQP), even if the technology is not successful, is not to be undervalued and is worthy of investment. Mitigation can be achieved by strategically partnering with other players in the field over a range of technologies to distribute risk and share successes. These broad partnerships will help DND strengthen its own expertise while pursuing complimentary S&T objectives.

2.1 Establish and sustain strategic partnerships within government

The NRC is recognized amongst the world leaders in quantum S&T and is the Canadian government lead in coordinating and advising on quantum technologies. To begin, DND will form a strategic partnership with the NRC and will benefit through leveraging their world-class expertise, facilities, and formidable academic and industrial networks. Through collaboration with NRC, DND will remain continuously informed on the state-of-the-art and readiness levels of quantum technologies while simultaneously developing HQP within DND and connecting to the broader Canadian and global quantum community. This will in turn enable DND to continuously assess the defence and security implications of quantum technologies in order to inform and steer the implementation of DND quantum capabilities, programs, and policies. Reciprocally, NRC will benefit from access to pressing defence and security problems, allowing them to position their research programs appropriately to address priority Canadian and allied defence and security needs.

Through this partnership, the NRC's Industrial Research Assistance Program (IRAP) allows for a particularly valuable function. IRAP has a considerable business intelligence unit and can play a significant role by connecting defence industry and government, identifying and accelerating innovative and marketable defence R&D projects focused on filling defence and security gaps, and facilitating quantum technology transfer.

DND will also work with other government departments through the existing Quantum Science and Technology Assistant Deputy Minister (ADM) Coordination Committee. The objective of the ADM committee is to strengthen federal government efforts by coordinating and leveraging federal government expertise into collaborative projects and



Credit: University of Waterloo

partnerships for the benefit of multiple organizations. For example, the partnership between DND and Public Safety Canada through Defence Research and Development Canada (DRDC), the Centre for Security Science (CSS) and the Canadian Safety and Security Program (CSSP), can be leveraged in cases where quantum technologies can be developed for Defence, Security, and Public Safety purposes. Another example is quantum computing, including quantum-resistant cryptographic algorithms, which will be monitored through DND's partnership with the Communications Security Establishment (CSE).

ACTION NO. 4:

Establish a strong strategic partnership with the National Research Council. Embed defence scientists at NRC; leverage their world-class expertise and networks to support the development and delivery of projects.

2.2 Establish DND, through Defence Research and Development Canada, as a strong federal partner in Canada's quantum ecosystem

DND will work closely with federal departments, academia, and industry to advance Canadian quantum technologies in areas of national interest. In addition to investments through DND's existing S&T programs, DND will engage the quantum innovation system through mechanisms such as the Innovation for Defence Excellence and Security (IDEaS) program and the CSSP in order to help stimulate the growth and transition of promising work and foster the emerging Canadian quantum industry. Such programs will be utilized to test quantum technologies in challenges framed around defence and security problems, thus situating DND as a mainstay in the Canadian quantum landscape. Additionally, DND will play a key role in the development of a national quantum strategy in order to contribute to a focused national investment in Canadian quantum technologies for defence. Doing so will support Canada's defence and economic security through the development and sustainment of a sovereign industrial capability.

ACTION NO. 5:

Position DND to drive innovation in quantum S&T for defence capabilities through national collaboration and partnership with the Department of Innovation, Science, and Economic Development Canada (ISED) for investment in quantum science, technology, and innovation.

2.3 Leveraging international defence peers

Canada's Five Eyes (FVEY) defence counterparts have strong national quantum programs. Other North Atlantic Treaty Organization (NATO) allies are also investing significantly in quantum technologies. DND will collaborate with international defence peers with emphasis placed on a burden sharing approach to accelerate the development and integration of quantum-based technologies suitable for the defence, safety, and security environments. In conjunction with defence and security peers, DND will participate in developing and sharing emerging standards to ensure interoperability, capability assurance, and robustness for harsh environments [6]. A healthy integrated DND quantum S&T program bringing forward impactful R&D will allow Canada to access and contribute to allied world-class quantum R&D.

ACTION NO. 6:

Invest in world-leading quantum S&T so that it can access, leverage and contribute to the development of mutually-beneficial quantum technologies internationally, accelerating quantum technology development to allied benefit.

Pillar 3:

Bring coherence to quantum S&T investments across DND/CAF

The Department of National Defence has already begun investing in quantum technologies through the internal integrated S&T program. Continuing Defence investment must align with Canada's defence policy, *Strong, Secure, Engaged* [7] and target areas requiring stimulus to move towards Defence capabilities. Investment should follow an informed quantum technologies roadmap and engage the quantum innovation ecosystem through challenges that align with Defence S&T priorities. This investment should include safeguards to protect the research, IP and technologies that result, in alignment with the open science guidelines outlined by the Government of Canada.

3.1 Build capacity for quantum technology exploitation

DND will build and maintain a core team of highly qualified personnel with thorough knowledge of quantum technologies and of the Canadian defence and security context. An extended team will include defence science subject matter experts (SMEs) who are delivering on current Defence S&T programs, and will have the critical mass to be literate across all areas of quantum technologies, how they relate to Defence needs, and how they may best be exploited.

3.2 Strengthen evidence-based planning for quantum technologies

To best anticipate, adapt, and act in a rapidly changing quantum technology and application space, DND requires up-to-date science advice to be communicated and integrated into Defence capability planning. DND will identify, monitor, and evaluate the impact of emerging quantum technologies on existing defence systems and approaches (defensive, offensive, countermeasures and enablers) and integrate this analysis to inform on both the defence opportunities presented and the threat landscape. DND will also capitalize on partner organization technology road mapping and foresight and leverage analysis from extramural national and allied Defence S&T organizations to further DND/CAF understanding and exploitation of relevant emerging quantum technologies.

The evolving departmental quantum technology roadmap will take into account the relative strengths and focus areas of national and international peers' own quantum technological interests and developments. This technology roadmap will be used to inform and align Defence science, technology, and innovation investments with defence priorities and amplify their value from a coalition perspective.

ACTION NO. 7:

Strengthen DND/CAF's internal quantum S&T capacity to assess the relevance and impact of quantum technologies in a defence and security context; advise on quantum science, technology, and innovation investments, including recommending areas that require augmented internal capacity to integrate them, and enable DND to contribute to and leverage allied efforts.

CONCLUSION

Quantum technologies will

transform

the defence and security landscape. The pillars outlined in this strategy support important defence outcomes, including ensuring Canada is not technologically outpaced and outmatched by potential adversaries. A focus on quantum sensing will support DND's unique mandate of ensuring Canadian sovereignty over an enormous land mass, including aerospace and maritime approaches. Early Defence engagement with the Canadian quantum S&T ecosystem will ensure Defence-specific priorities, such as resilience, assurance, and countermeasures are understood and addressed as the technologies come to maturity. Strategic partnerships with the NRC and with NORAD, Five Eyes, and NATO allies will leverage existing national and international strengths to deliver on collaborative projects spanning all defence-relevant quantum technologies. Focused, informed, and well-planned investments will more rapidly and efficiently lead to new and enhanced defence capabilities.

DND is in a position to responsibly drive and expedite development of emerging quantum technologies through targeted science, technology, and innovation investments with academic, industrial, and governmental partners. With its own quantum S&T strategy in place, DND is also positioned to play a leading role in a national quantum strategy that will enable both the highly-trained workforce and the investment to ensure Canada builds a thriving domestic quantum sector. The economic security of this sector will be a national priority in which Defence will play a key role.

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ACRONYMS

ADM	Assistant Deputy Minister
CAF	Canadian Armed Forces
CSE	Communications Security Establishment
CSS	Centre for Security Science
CSSP	Canadian Safety and Security Program
DND	Department of National Defence
DRDC	Defence Research and Development Canada
FVEY	Five Eyes
GDP	Gross Domestic Product
GPS	Global Positioning System
HQP	Highly Qualified Personnel
IDEaS	Innovation for Defence Excellence and Security Program
IP	Intellectual Property
IRAP	Industrial Research Assistance Program
ISED	Innovation, Science, and Economic Development Canada
NATO	North Atlantic Treaty Organization
NORAD	North American Aerospace Defense
NRC	National Research Council
PNT	Positioning, Navigation and Timing
R&D	Research and Development
S&T	Science and Technology
TRLs	Technology Readiness Levels