EXPLORING RESPONSIBLE QUANTUM INNOVATION EFFORTS IN CANADA AND THE WORLD

SUMMARY: We assess global quantum technologies efforts in the Responsible Innovation framework and how Canada leads or lags in development and regulations.

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The global landscape for quantum technologies (QTs) is rapidly changing, and proper understanding of their impact and subsequent regulations need to match this pace. A Responsible Innovation (RI) approach and guiding principles have been proposed to accompany this development. We examine practical efforts globally and in Canada, from industry to research to governments, and analyze the current status of quantum technological advances under the RI framework. We analyze and compare what is being done internationally, identify gaps in the Canadian strategy, propose initiatives to fill those gaps, and highlight areas where Canada is leading or where more work is needed.

The widespread real-world impact that quantum devices will have in the near future demands attention from various sectors of society, not only those interested in research and commercialization. In response to this, international efforts have started to address the needs and consequences of the use of quantum technologies [1].

An integral part of the allocation of quantum technologies in society is consideration of the ethical implications of their use, operation, and manufacture. Do countries responsible for the research and implementation of such devices take these implications into account as they lay out their roadmaps for development? How does Canada fit in this larger picture?

We review efforts from governments, private initiatives, research groups, and grants to answer these questions in the frame of responsible innovation [2,3]. Whenever possible, we highlight verifiable output displaying the efforts: events, technical papers, policy documents, etc. We use Kop *et al*.'s Ten Principles [2] to determine the grounds for comparison, and survey the relative frequency with which each of the Principles of responsibility are addressed within a National Quantum Strategy (NQS).

We search and collect in NQS documents the keywords defined in Table 1. This is followed by verifying, within context, whether the sentence containing the keyword addresses the corresponding Principle.

The accounted quotes may include similar words, e.g. "ethics" and "ethical". Finally, the mentions to each Principle are counted and compiled in Table 2.[1] We use the CIFAR report [1] to decide what document is an NQS, and we include updated references by Qureca [5] and based on other web searches. We do not attempt to define new criteria.

We refer to each of the ten Principles in an abbreviated manner: P01 (**Table** 1), for example, refers to Principle 1 (Information security). Additional remarks on the choice of NQS documents are discussed in the next section.

INTERNATIONAL

We analyze the NQS documents listed in Table 2 and display the keyword search results there.

We see that all NQS documents roughly follow the same pattern, which reflects the context and time when these documents were crafted, with the most pressing issues of information security (P01) and race to technological edge (P03) heading the counts, and with issues of Innovation (P08) following. Occupying a negligible portion of each NQS, we have Dual Use (P02), Quantum Gap (P04), and IP (P05). A possible explanation is that both Dual Use and IP regulations may be covered in more specialized documents, when contrasted with Information Security due to its national security implications. Furthermore, while the absence of mentions of the Quantum Gap may be explained by the country-specific scope of these documents, it is an example of terminology that has only been introduced recently.

We expect that growing attention to societal problems will be given when QT reaches commercial application with practical use cases. These results suggest that the Principles of Quantum Gap, Inclusion, and Education (P04, P06, P10), which can inform what problems are of Societal Relevance (P07), are lagging behind.

The development of QT happens in an effervescent ecosystem, as demonstrated by the website for the International Year of Quantum (IYQ) [6], but a lot still needs to be addressed. The Quantum Economy Blueprint [7], a report guiding responsible development, raises the problem of the Quantum Divide (P04) between developed and Majority World countries as one that needs addressing. The IYQ map gives a glimpse of this: the number of activities in North America and Europe largely outnumber the ones in Latin America, Africa, and Asia. As we will argue in the following sections, research and an active stance must be taken on this, and with regards to other Principles that received less attention in

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[1] We follow the methods used in Lesher *et al*. [4] to compile Figure 2.

TABLE 1

List of principles, a short description taken directly from,[2] and
our choices of Keywords for the keyword search.

#	Principle	Description	Keywords
01	Information Security	Make information security an integral part of QT.	Security; cybersecurity; threat; attack.
02	Dual Use	Proactively anticipate the malicious use of quantum applications.	Dual use; usage; malicious; hazard; warfare; unintended.
03	Quantum Race	Seek international collaboration based on shared values.	Race; international; collaboration.
04	Quantum Gap	Consider our planet as the sociotechnical environment in which QT should function.	Gap; quantum divide; global; world; unequal; disproportionate; fair.
05	Intellectual Property (IP)	Incentivise innovation while being as open as possible and as closed as necessary.	IP; Intellectual Property; open source.
06	Inclusion	Pursue diverse R&D communities in terms of disciplines and people.	Inclusion; DEI or EDI; equity; diversity.
07	Societal Relevance	Link quantum R&D explicitly to desirable societal goals.	Social; benefit.
08	Complementary Innovation	Actively stimulate sustainable; cross-disciplinary innovation.	Innovation; adaptation; adoption; progress.
09	Responsibility	Create an ecosystem to learn about the possible uses and consequences of QT applications.	Responsible; ethics; consequences; risk.
10	Education and Dialogue	Facilitate dialogues with stakeholders to better envision the future of QT.	Education, dialogue, outreach, science communication, general public, engage

the NQS documents, as we move forward. Furthermore, in an agenda to be fulfilled by 2030, the United Nations define Sustainable Development Goals (SDGs). It has been argued that QTs have the potential to be used to address the SDGs [8-10] (P07), and governing bodies that subscribe to this agenda should adopt policies reflecting this potential [11].

TABLE 2

Assessment of the presence of Principles in National Quantum Strategies [23-32]. Numbers indicate how many quotes address each Principle, shown as a percentage of the total number of quotes in that document. These documents were chosen by referring to the countries with NQS ready or in development. We disregard NQS documents that are not in English or not publicly available.

National Quantum Strategies	01	02	03	04	05	06	07	08	09	10
Australia	10%	0%	27%	0%	4%	12%	10%	6%	16%	14%
Canada	11%	1%	40%	1%	2%	5%	14%	9%	9%	9%
Denmark	22%	2%	26%	1%	3%	2%	12%	18%	9%	4%
Ireland	23%	1%	17%	1%	2%	6%	13%	24%	7%	5%
Netherlands	19%	0%	15%	1%	0%	0%	29%	16%	7%	12%
South Africa	30%	0%	22%	0%	8%	3%	5%	15%	0%	17%
South Korea	24%	1%	19%	2%	1%	6%	13%	25%	3%	6%
United Kingdom	16%	0%	20%	0%	4%	4%	15%	22%	14%	4%
United States	32%	2%	19%	0%	6%	0%	6%	14%	5%	16%

Before focusing on Canada, we point out that an integral part of the international efforts is led by specialists and addresses a large set of problems that can be classified under the RI Principles. Some examples are QT activities in the G77[2] plus China (P04), a study commissioned by the Quantum Delta program [12]. Research groups are starting to tackle the field of "quantum humanities" (P07–09), with examples in Europe, Asia, and North America [13-17] and to aid in this, quantum experts must have a strong grasp of QT, which is achieved by promoting Education and Dialogue (P10) [18]. Research on resource costs for QT, and how QT can address climate change are also integrated under socially relevant problems (P07) and are being investigated [19-20]. Ultimately, QT must not be considered in isolation; its interaction with other important emerging technologies is paramount, in particular artificial intelligence, and it must ideally be done in cross-disciplinary fashion (P08) [21,22].

CANADA

The Canadian NQS aims to establish Canada as a world leader on the quantum development stage, to boost national cybersecurity with post-quantum cryptography incentives, and to support the adoption of quantum sensing technologies [24].

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[2] The Group of 77 (G77) is an intergovernmental organization of developing countries within the United Nations framework aimed at articulating their shared economic interests. "G77 plus China" refers to the extra consideration of China.

Although all the Principles outlined in the RI framework are discussed in the NQS, our analysis (see Table 2) revealed that Canada's initiatives align primarily with Quantum Race (P03) and Societal Relevance (P07). In particular, Canada placed a stronger emphasis on P03 than any other country surveyed, demonstrating a particular focus on international collaboration for successful quantum development. In contrast, less attention was given to Inclusion (P06), Complementary Innovation (P08) and Education and Dialogue (P10) than in peer countries. To align more closely with an RI framework, greater attention must be paid to these Principles.

Bolstering one Principle often reinforces others. For example, increased commitment to Inclusion (P06) and Education (P10) is needed to properly bring Societal Relevance to light (P07). After all, it is difficult to identify the most relevant societal problems for quantum technology without first strengthening diversity and engagement in the workforce and the general public space. At the same time, it is important to consider the potential trade-offs from Principle interactions. For one, increasing open access (P05) while maintaining a competitive edge in the quantum race (P03) and preserving national cybersecurity (P01) poses a real strategic challenge. It is important to keep this balancing act in mind when making these changes.

Although still in its infancy, the Canadian responsible quantum innovation landscape has already begun to develop, with some initiatives making use of government funding. One such organization is the Centre for Responsible Quantum Innovation and Technology (CRQIT) in British Columbia. With the principal goal of nurturing responsible quantum innovation on a national and international level (P02, P03, P09), the CRQIT's efforts have a broad span. This includes advisory work on EDI policies in Canada's quantum hubs and engagement with UNESCO [33].

A project sharing similar goals is underway at the Institut Quantique. This work, created with the realities of research and entrepreneurial development in mind, aims to create tools to encourage those in the quantum ecosystem to analyze the potential societal impacts of their work throughout its process, rather than after the fact [34] (P02, P07, P09). Another important facet of the Canadian RI landscape has been enabling broader participation in technological development. For instance, Open Quantum Design is a non-profit organization in Waterloo creating an open-source quantum computer using trapped ions [35] (P09, P10).

Finally, Canadians are also contributing to the growing international conversation on responsible quantum innovation. The Centre for International Governance Innovation (CIGI), based in Waterloo, has produced a number of publications exploring Canada's quantum ecosystem through the lens of policy [36-39]. In 2025, CIGI organized the Think7 (T7) process as part of Canada's G7 presidency, bringing together experts from around the world to develop policy briefs that will inform G7 decision-making (P03) [40,41].

FUTURE PROSPECTS

Canada's evolving quantum ecosystem offers a timely opportunity to align its national initiatives with RI Principles. This section outlines recommendations for Canada to strengthen its strategic position while ensuring ethical, secure, and sustainable development of quantum technologies.

To begin, to guarantee a science-based adoption system, the government should increase efforts to educate policymakers and companies about quantum technologies (P10). Well-defined standards assessing the development, security, and effectiveness of quantum systems can only be properly defined if those creating them have sufficient technical understanding. For instance, the government could hire physicists to deliver workshops to help these professionals build their quantum knowledge [42]. Conversely, it is also crucial for researchers to consider the social consequences of their work, and one way to do this is by learning about policy. This will increase engagement between the public, private, and academic sectors, clarify security requirements, and increase trust in government regulation (P08, P09).

Partnerships with allies should continue to be nurtured to share the responsibilities of advancing quantum technology (P03). Moreover, Canada has the opportunity to improve its position as a leader in quantum development by actively pursuing inclusive relations with developing nations and pushing for a shared-values system. Building such associations gives Canada leverage in negotiations, provides a competitive edge in the Quantum Race (P03), and directly lessens the Quantum Divide (P04). Throughout this work, it is also important to remain aware of research security risks (P01).

In our analysis, we found that most NQSs placed less emphasis on social Principles like P06. In Canada's case, although the importance of social science research for quantum was discussed, no funding was assigned to it. We suggest that a portion of NQS funding should be allocated to social science research to connect the technical advancement of the quantum ecosystem to ethical and regulatory considerations [43].

It is also important to encourage private companies to share insights from real-world testing, thus fostering a more collaborative, open, and responsive quantum ecosystem (P05). Moreover, both the public and private sectors should map out supply chains for future quantum technologies and take steps to protect critical hardware from potential threats. This work protects quantum infrastructure (P01) and pushes nations to navigate dependencies and maintain competitive resilience in the global quantum landscape (P03).

Although this article focuses on Canada, an interesting generalization would be to analyze the differences in focus between the Global North and South. We also hope that the discussions in this paper will motivate physicists to become involved in ethics and policy, thus ensuring the development of directives that are both compliant with RI and scientifically accurate.

ACKNOWLEDGEMENTS

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