

# 10 Principles for Responsible Quantum Innovation

Mauritz Kop<sup>1</sup>, Mateo Aboy<sup>2</sup>, Eline De Jong<sup>3</sup>, Urs Gasser<sup>4</sup>, Timo Minssen<sup>5</sup>, I. Glenn Cohen<sup>6</sup>, Mark Brongersma<sup>7</sup>, Teresa Quintel<sup>8</sup>, Luciano Floridi<sup>9</sup> and Raymond Laflamme<sup>10</sup>

<sup>1</sup> Stanford Law School, Stanford University, USA

<sup>2</sup> Faculty of Law, University of Cambridge, Cambridge, UK

<sup>3</sup> Institute for Logic, Language and Computation at the University of Amsterdam, The Netherlands

<sup>4</sup> TUM School of Social Sciences and Technology at the Technical University of Munich, Germany

<sup>5</sup> CeBIL, Faculty of Law, University of Copenhagen, Copenhagen, Denmark

<sup>6</sup> Harvard Law School, Harvard University, Cambridge, USA

<sup>7</sup> Material Science and Engineering, Stanford University, USA

<sup>8</sup> European Centre on Privacy and Cybersecurity (ECPC), Maastricht University, The Netherlands

<sup>9</sup> Oxford Internet Institute, Oxford University, Oxford, UK

<sup>10</sup> Institute for Quantum Computing, University of Waterloo, Canada

E-mail: mkop@stanford.edu

## Abstract

This paper proposes a set of guiding principles for responsible quantum innovation. The principles are organized into three categories: *safeguarding*, *engaging*, and *advancing* (SEA), and are grounded in the values of responsible research and innovation (RRI). Utilizing a global equity normative framework, we link the Quantum-SEA categories to promise and perils specific to quantum technology. The paper operationalizes the Responsible Quantum Technology framework by proposing ten actionable principles to help address the risks, challenges, and opportunities associated with quantum technology. Our proposal aims to catalyze a much-needed interdisciplinary effort within the quantum community to establish a foundation of quantum-specific and quantum-tailored principles for responsible quantum innovation. The overarching objective of this interdisciplinary effort is to steer the development and use of Quantum Technology (QT) in a direction not only consistent with a values-based society but also a direction that contributes to addressing some of society's most pressing needs and goals.

Keywords: Responsible Quantum Technology, Quantum Safeguarding, Engaging & Advancing, Quantum-AI Ethics & Governance, Regulation, Responsible Quantum Innovation, Quantum R&D, Responsible Research and Innovation (RRI)

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## 1. Introduction

As we stand on the cusp of the second quantum revolution, we face unprecedented opportunities and challenges in the field of quantum technology (QT) [1]. A recent empirical landscape study showed an exponential increase in the number of patents directed to QT inventions, illustrating the sheer pace and breadth of quantum innovation [2]. With the potential to revolutionize computation, cybersecurity, communication and sensing, QT and its anticipated future uses are poised to redefine the way we understand and interact with the world. Yet, with such power shifts fueled by technological advancements comes the responsibility to innovate thoughtfully and conscientiously. But what does it mean to develop and use quantum technology responsibly? How do we ensure that this transformative technology benefits society, minimizes risks, and remains ethical?

As is the case with large AI models with emergent capabilities such as generative adversarial networks (GANs), the rapid development and deployment of QT demands a proactive, holistic and principle-based approach to ensure that that quantum innovation is managed responsibly in order to ensure that its potential is realized in a manner that is beneficial to society.

QT is not new. However, the rise of second-generation (2G) quantum technologies has the potential to revolutionize many fields. By directly harnessing unique quantum mechanical properties such as superposition, entanglement, and tunneling (Box 1), 2G QT opens up a myriad of applications that will likely impact society at large [27]. Given QT's inherent ability to solve complex problems that classical technologies struggle with, the recent progress of QT promises a new era of scientific advancements and industrial applications. This

includes QT/AI hybrids [13] where the quantum computer is used as an accelerator to solve computationally intractable problems for classical computers and AI, such as simulation [17] of quantum chemistry to accelerate novel drug development. That said, alongside these beneficial uses, there are material risks. For instance, quantum computing also has the potential to break the RSA encryption systems that we currently use to ensure privacy across internet communications [20]. Thus, alongside the vast potential for innovation, there are significant ethical, social, and QT governance implications that must be addressed to ensure responsible growth and adoption [26].

A recent study analyzed the risk posed by quantum computing to information security as an illustrative example of the challenges ahead and introduced a Responsible Quantum Technology (RQT) framework that incorporates ethical, legal, social, and policy implications (ELSPI) into the quantum R&D process [16]. The authors argued that quantum innovation should be guided by a methodological framework for Responsible QT, aimed at jointly 1) *safeguarding* against risks by proactively addressing them, 2) *engaging* stakeholders in the innovation process, and 3) *continue advancing* QT; and called for operationalizing the RQT framework by establishing a set of principles to guide future quantum innovation.

### Box 1: Quantum exceptionalism

Superposition, entanglement, and tunneling are three central principles in quantum physics [41]. They refer to the phenomena of particles existing in multiple states at the same time (*superposition*), particles interacting in a mutually dependent way even when they are separated by great distances (*entanglement*), and the ability of particles to cross energy barriers (*tunneling*). 2G QTs are based on *directly harnessing* such quantum phenomena for practical applications such as quantum sensing, quantum computing and quantum communications [1]. This makes QTs fundamentally different from those based on classical physics, and could imply a ‘quantum advantage’ over our existing technologies.

In this paper, we build upon the RQT framework by proposing ten guiding principles to help navigate the complex terrain of QT development and application. Organized into three categories – safeguarding, engaging, and advancing - these principles are grounded in the values of responsible research and innovation (RRI) [6], emphasizing anticipation, reflection, openness, transparency, responsiveness, diversity, and inclusion. Utilizing a global equity normative framework, we link the Quantum-SEA categories to the opportunities and challenges specific to quantum technology and provide

actionable recommendations for their adoption, actively steering the field into a direction congruent with values-based societies [21].

Analytically, the principles are aimed at ensuring that ethical, legal, cultural, socio-economic, and philosophical dimensions [25] are identified and discussed while QTs are still shapeable [7]. From a normative perspective, the objective is to capture and promote beneficial opportunities expected from quantum innovation while managing potential downsides by putting into place technical, organizational, and policy guardrails appropriate to the risk. At present, many of QT’s ramifications seem hypothetical, and indeed many societal implications remain unknown. It is precisely this moment, when the state of technology is still in flux, that we have a unique opportunity and responsibility to shape its maturity towards desirable societal outcomes [5]. The ten principles we propose in this article should be considered as a starting point for such an interdisciplinary effort.

## 2. Safeguarding Principles

The safeguarding category of principles supports proactive risk management and responds primarily to the RRI values of *Anticipation & Reflection*. In particular, the safeguarding principles tackle proactive risk management, delving into information security, dual-use, and the quantum race. By stressing the importance of risk-based quantum impact assessments (QIA), anticipating malicious use, and fostering international collaboration based on shared values, these principles help build a solid foundation for responsible QT innovation.

### 1. Information Security: Make information security an integral part of QT

*Principle 1* embraces information security as an integral part of QT. This perspective is considered the starting point for addressing information security risks including threats to data privacy. Quantum algorithms have the potential to break current cryptography protocols [2,8], hence threatening the information security of existing information technologies (IT) [4]. This would destabilize society - as it could expose extensive swaths of information currently regarded as private and confidential - ranging from sensitive personal data to financial sector and national security information assets. [3, 4] Innovators share the responsibility for the inherent impact of their creations. Thus, research on and development of quantum computing should be accompanied by risk-based quantum impact assessments (QIA) focused on information security risks and implementing controls to mitigate such risks. This includes the implementation of state-of-the-art information security management systems (ISMS) such as

Category	Topic	Aim	RRI-value	Principle
<b>Safeguarding</b>	Information security	Addressing security threats	Anticipation & Reflection	1. Consider information security as integral part of QT
	Dual use	Addressing risks of dual use	Anticipation & Reflection	2. Proactively anticipate the malicious use of quantum applications
	Quantum race	Addressing a winner-takes-all dynamic	Anticipation & Reflection	3. Seek international collaboration based on shared values
<b>Engaging</b>	Quantum gap	Engaging states	Openness & Transparency	4. Consider our planet as the sociotechnical environment in which QT should function
	IP	Engaging institutions	Openness & Transparency	5. Be as open as possible and as closed as necessary
	Inclusion	Engaging people	Diversity & Inclusion	6. Pursue diverse R&D communities in terms of disciplines and people
<b>Advancing</b>	Societal relevance	Advancing society	Responsiveness & Adaptation to Change	7. Link quantum R&D explicitly to desirable societal goals
	Complementary innovation	Advancing technology	Responsiveness & Adaptation to Change	8. Actively stimulate sustainable, cross-disciplinary innovation
	Responsibility	Advancing our understanding of responsible QT	Responsiveness & Adaptation to Change	9. Create an ecosystem to learn about the possible uses and consequences of QT applications
	Education and Dialogue	Advancing our collective thinking and education about QT and its impact.	Responsiveness & Adaptation to Change	10. Facilitate dialogues with stakeholders to better envision the future of QT

ISO27001 to protect information assets from a particular QT R&D program. Notably, this requires the implementation of quantum-safe information security controls that can ensure our information systems and communications are resistant to attacks by cryptographically relevant quantum computers (QC) [4]. At a minimum, QC should not advance more rapidly than the availability of quantum-resistant cryptographic algorithms. Such algorithms must be safe and secure against cryptanalytic attacks by QC that employ quantum algorithms breaking common public key cryptographic systems in use

today [8]. This calls for researching and investing in post-quantum cryptography initiatives, as well as post-quantum information security programs. Furthermore, the possibility of implementing a strategy “store now, decrypt later” should provide incentives to start replacing our existing cryptosystems for critical information assets with post-quantum cryptographic systems that are resistant to attacks by quantum algorithms as early as possible [16].

## 2. Dual Use: Proactively anticipate the malicious use of quantum applications

*Principle 2* deals with the proactive anticipation of the malicious use of quantum applications. It aims to prevent the harmful use of QT. Most applications of QT may be used for diverse civilian and military ends (“dual use”) [23]. QT innovations could be used to serve society through applications that are relevant to today’s grand challenges of providing a prosperous, safe, sustainable [35], and connected world, -which could well include military secondary usage and deterrence by governments- but when used by malicious parties it can pose a serious material threat. This dual use character is not unique to QT and has been raised with technologies as diverse as gene editing, biometrics, and nuclear energy. However, as with the closely related case of nuclear power, the stakes with QT are exceptionally high [9]. QT are categorically different from the technological improvements that we have seen since WWII because of the nature of the advantages that “quantum dominance” could entail. Imagine being able to crack RSA-2048-bit encryption in 10 seconds by implementing Shor’s algorithm in a fault-tolerant QC [8]. The quantum pioneers could achieve an advantage that is orders of magnitude superior to their classical counterparts resulting in vastly superior computation (optimization, search, and cryptography), communication, and measurement [16]. Consequently, both innovators and regulators [28] need to anticipate potentially malicious use of QT by (1) utilizing both technology forecasting [42] and horizon scanning techniques [37] anticipating novel dual use quantum use cases, in unison with (2) implementing appropriate safeguards at the initial stages of the technology readiness level (TRL) [2]. Such assessments should be conducted by governments and at the organizational level and linked to certification by independent notified bodies in connection with market introduction. For example, by conducting a dual-use risk assessment examining how a particular QT R&D program or innovation could be used for terrorist or criminal ends, potential risks could be anticipated. This would offer the opportunity to implement appropriate safeguards - such as import/export controls or requiring technological “kill switches” - to mitigate specific inherent risks for a particular QT application throughout its lifecycle so that residual risks are acceptable [3].

## 3. Quantum Race: Seek international collaboration based on shared values

*Principle 3* seeks international collaboration based on shared values. Given larger geopolitical dynamics, investments in QT R&D take the shape of a global arms race where companies and countries with incompatible ideologies or fundamental values compete, and where intellectual

property rights (IPRs), trade secrets, and antitrust enforcement policies are becoming important assets in national and regional strategies. Such competition between systemic rivals can be a driver of innovation. However, this race for national success could also thwart progress if it stymies the opportunity to join forces, especially among partners with mutually aligned values. The prospect that the forerunner in the field will make crucial decisions about the design and use of QT bears a high risk. There is also a risk that if QT dominance enters a geopolitical race dynamic, the incentives will skew away from ethically-appropriate one step at a time development; it is easy for countries to imagine that as bad as it would be to fail to build in safeguards aimed at ELSPI, it would be far worse to lose the dominance race. In economic, political, and ethical terms, preventing a winner-takes-all dynamic requires establishing broad partnerships [36]. States and research institutions should seek international partnerships based on shared values (such as liberal-democracy, human rights, and the rule of law), to accelerate quantum R&D and to actively shape its direction. This is particularly relevant during the early phases of QT development. In line with this aim, fundamental quantum research (TRL 1-3) and pre-competitive (TRL 4-7) core/base layer QT should be as openly accessible as possible, and as closed as necessary from a national, regional, and economic security perspective. Ideally, knowledge sharing should be incentivized without ignoring crucial security and resilience risks (see Principle 5).

## 3. Engaging Principles

The engaging principles aim to create an inclusive environment for quantum R&D. From bridging the quantum gap to managing intellectual property and cultivating an inclusive R&D environment, these principles ensure that QT benefits reach far and wide. This category of the principles aims to create an inclusive environment for quantum R&D, at the level of countries, organizations, and individuals and responds to the RRI values of *Openness & Transparency* and *Diversity & Inclusion*.

## 4. Quantum Gap: Consider our planet as the sociotechnical environment in which QT should function

*Principle 4* advocates considering our planet as the sociotechnical environment in which QT functions. It points to our global interconnectedness and aims to promote equitable and fair access to QT (Quantum for All). As quantum R&D is highly complex, infrastructure dependent, and expensive, there is a risk that the technology, without proactive interventions, may remain accessible only to an elite, creating a gap between the “haves” and “have-nots.” This “quantum-divide” is not only morally problematic but

also suboptimal from an innovation and sustainability point of view. Actively bridging the quantum divide could contribute to achieving desirable goals, such as leveraging the power of QT in enhancing drug discovery. It could also enable helping address (ecological) sustainability challenges ranging from water management, hyper precision weather forecasting, and lowering the carbon footprint of classical computing and data processing, to development of advanced solar cell concepts, clean fuels, and a variety of chemistries that provide us with fertilizers and food. It could facilitate creating the required technical infrastructure more effectively and on a larger scale. What's more, competition law principles and enforcement actions [36]- in concert with respecting IP and allied rights including trade secrets, state secrets, and fair-trade conditions - should contribute to fair and equitable access to QT and solve market failures (see Principle 5) [2]. A permanent forum for transdisciplinary dialogue between Majority World countries and the Global North should be established, being mindful that current epicentres of quantum R&D are in a few restricted environments. It should be a shared R&D objective to develop quantum standards [45], applications, and infrastructure that are inclusive and equitable both within and across nations.

#### *5. Intellectual Property: Incentivise Innovation while being as open as possible and as closed as necessary*

*Principle 5* should aim to incentivise quantum innovation and achieving appropriate degrees of openness in quantum R&D. RRI benefits from sharing insights and approaches [31]. This is especially the case in QT, as only a relatively small number of key players could influence and decide the direction of quantum innovation. A recent study explored the IP landscape of QT and the role of patents in incentivizing public disclosure. It found that the patent system is currently encouraging public disclosure in the field of QT, despite trade secrets potentially being a more commercially viable IP option at this stage. This preference for trade secrets can be attributed to the early-stage nature of many QTs, the market structure, and emergent business models [2]. This research also indicated that large-cap incumbents with leading market positions tend to benefit from and may favour proposals that weaken patent rights, while new quantum technology entrants are more likely to benefit from stronger patent rights to not only protect their inventions but also attract investment [2]. Notably, in addition to promoting public disclosure, an important aspect of the patent system is the concept of "secrecy orders." In certain instances, particularly when dealing with inventions with direct applications to defence and national security, the US patent system allows for inventions to be classified and subject to secrecy orders. This means that the disclosure of these inventions would be restricted as their publication or dissemination could be detrimental to national security. While this practice is necessary in some cases, it also highlights the need for a careful balance between promoting

innovation through public disclosure and protecting sensitive information. Given the findings of the aforementioned patent landscape study [2], we recommend that public policy considerations for responsible quantum innovation should take into account the results of evidence-based (empirical) results of IP studies when designing, assessing, and proposing legal and regulatory reforms related to quantum technologies. Additionally, we suggest that further research is needed to clarify the role of IP rights and push incentives in different sectors and technologies, such as quantum sensing, simulation, computation, and communications, to better inform responsible innovation strategies in the quantum domain. The role of secrecy orders in the patent system should be carefully considered to strike a balance between promoting innovation and protecting sensitive information [2].

While IP continues to play an important role for incentivizing quantum innovation, beyond the NISQ (noisy intermediate-scale quantum) era, it may be necessary to balance it with other legal regimes, such as competition law [36]. It is essential to tailor existing IP policy -including debates about its reform- to QT and consider it in the context of national and regional security strategies [22]. Funders should promote quantum-open innovation [10, 30] and democratize access to QTs [12, 43] at the base layer while enabling innovators to obtain sufficient levels of IP protection for their inventions to attract the necessary investment [2]. This could be accomplished by providing cloud-based access to quantum computing infrastructure, allocating educational resources to learning quantum skills and programming (see Principle 9), implementing progressive Standard Essential Patent (SEP) policies [44] for technologies embedded in QT interoperability standards, and by building and deploying quantum algorithms using open-source software development kits. That said, an important aspect of this effort is also implementing best practices for safeguarding IP including preventing IP theft (see Principle 1), as well as addressing associated geostrategic and national security concerns (see Principle 2 & 3) [15]. This may require geographic-based restricted access to cloud-based QT and R&D, and targeted export controls that restrict access to key QT enabling technologies while minimizing disruption to fragile supply chains (see Principle 3) [4]. Among the tools to consider are the use of secrecy orders as part of the patenting process, export controls, and trade secrets.

#### *6. Inclusion: Pursue diverse R&D communities in terms of disciplines and people*

*Principle 6* calls for an inclusive and participatory R&D environment, which includes a diverse R&D community in terms of disciplines and people. Anticipating and addressing considerations about Quantum-ELSPI from a broad range of perspectives at an early stage is vital. Later in the development

lifecycle, changes to design or use are much harder to implement. Engaging a group of people that is diverse in cultural and professional backgrounds during the R&D phase can prevent potentially irreversible harm and contributes to building a richer quantum workforce that capitalizes on talent in order to cultivate an inclusive view of the risks and values at play [7]. Thus, we recommend including different voices and perspectives during the R&D phase by (i) diversifying communities and teams in terms of discipline, experience, gender, nationality and ethnicity, (ii) implementing participatory public and private feedback mechanisms regarding the functioning of an application in practice, and (iii) closing STEM-related skills- and participation gaps in education sectors most important for QT.

#### 4. Advancing Principles

The advancing principles advocate for further QT innovation. Additionally, these principles provide a vision for QT's role in society, interpreting the RRI values of responsiveness and adaptiveness proactively. By underlining QT's societal relevance, complementary innovation, responsibility, and the importance of education and dialogue, these principles inspire a vision of a quantum future worth striving for. This category of principles is aimed at envisioning the role of QT in society, thereby interpreting the RRI values of *Responsiveness & Adaptive to Change* proactively, centering the social environment in which QT will be embedded.

##### 7. Societal relevance: Link quantum R&D explicitly to desirable societal goals

*Principle 7* encourages explicitly directing quantum R&D towards desirable societal goals such as the UN Sustainable Development Goals. It aims at unlocking the potential that QT offers for the benefit of humanity and our planet. That said, it recognizes that further R&D and investment is needed to advance “base-layer” [32] quantum technologies including quantum sensing, quantum computing, and quantum communications. These enabling fundamental building blocks require significant further development and investment in order to unlock their potential across application domains. The considerable promises of QT come with the responsibility to apply them wisely. At a minimum, quantum applications must refrain from consolidating or exacerbating existing problems, such as inequality. Beyond a “do no harm” ethical baseline, we advocate that innovations that explicitly link QT innovation to society's grand challenges of providing a safe,

sustainable, and prosperous world should be incentivized. This includes, for instance, using QT to lower the cost of advanced computer access for the world's poorest countries. As the overall objective of public and private funding policy, a mission-driven approach can be adopted to encourage R&D programs [24] that focus on pressing societal goals and prioritize them, either as a matter of design choices or envisioned uses. Such socially conscious funding schemes could include tailored programs as part of national science foundations.

##### 8. Complementary Innovation: Actively stimulate sustainable, cross-disciplinary innovation

*Principle 8* seeks to stimulate sustainable, cross-disciplinary innovation resulting in positive externalities and a virtuous cycle of progress comparable to that of the semiconductor industry.<sup>1</sup> QT are part of a larger sociotechnical ecosystem, as it *relies on* other technologies and research fields that QT, in its turn, can *enable or enhance*. Innovation should thus not only be envisioned in terms of applications for QT narrowly defined, but also in gestalt of hybrids with other technologies, such as machine learning and biotechnology [2]. To fully explore and take advantage of QT's potential, we recommend creating interdisciplinary research groups (see Principle 6), organizational R&D interfaces, and innovation agendas for QT that refer to potential cross-disciplinary applications and use cases [29].

##### 9. Responsibility: Create an ecosystem to learn about the possible uses and consequences of QT applications

*Principle 9* advances the creation of an ecosystem that fosters continuous learning about the possible uses and consequences of QT applications across contexts. The development and adoption of responsible QT over time requires feedback loops and other ways to track and assess the risks and opportunities of QT at the application level [11]. Given the current state of uncertainty, it is essential to create a learning ecosystem where QT can be applied to gain insights into ethical, legal, societal, and policy aspects and develop a deep understanding of what “responsible QT” entails. The goal is to ensure that this learning process occurs as early and responsibly as possible, avoiding any costs of learning being distributed unequally among different members of society, for instance already underserved or vulnerable communities. Flexible soft law instruments such as QT Sandboxes, QIA, certifications, benchmarks, international standards, and life cycle auditing [37] are among the tools to create a responsible learning ecosystem [12].

<sup>1</sup> A virtuous cycle, or positive feedback loop, requires ongoing private and public investments, research, development and engineering efforts, advancing QT

(including successful commercial QT applications) and attracting talent [38].

### 10. Education and Dialogue: Facilitate dialogues with stakeholders to better envision the future of QT

*Principle 10* encourages societal dialogue about the future of QT. It aims to engage society in actively envisioning and shaping that future. Providing accessible QT educational resources and facilitating discussions with stakeholders, enables a collective vision of a quantum future worth wanting. To be empowered to participate in such debates, people must have a basic understanding of QT and its uses. This is challenging, as the basics of QT (i.e., quantum physics) are not only highly complex but also counterintuitive. Our common-sense acquired by daily interaction with the macro world may be helpful to intuitively understand and use technologies based on classical physics such as cameras or cars, but less so for QT. Nonetheless, we should work on ways to familiarize people with QT so that they can join the discussion about its implications. Educational materials should be accessible to broad and diverse audiences, for example, by creating accessible online QT courses aimed at different levels of engagement from the general audience to the QT workforce (see Principle 9). In addition to larger societal debates, deliberative democracy models like stakeholder panels, shadow boards, citizen juries, or youth labs could serve as participatory mechanisms during both R&D and implementation phases to reflect on specific applications.

## 5. Balancing Safeguarding and Advancing Principles

Our proposed principles are not designed to be independent of each other. Instead, they are in an interactive relationship and their interplay can be optimized strategically to help create the conditions for sustainable quantum innovation over the long term. Perhaps counterintuitively, their overlap and interconnectedness are a feature and not a bug by broadening the available “solution” space and levers available to work towards responsible quantum innovation.

The *engagement* principles, for instance, play a crucial role in balancing the *safeguarding* and *advancing* principles by encouraging inclusivity and competition in quantum technology, while promoting awareness of QT issues in society through education and cross-sector dialog with stakeholders across sectors. The *safeguarding* and *advancing* principles, in turn, are two key components of a fit-for-purpose quantum technology regulatory framework. They are interrelated and should be jointly optimized to promote quantum innovation [33]. For instance, the safeguarding

principles helps manage the risks of dominant players achieving monopolistic competitive advantage by restricting access to essential quantum infrastructure, while the *advancing* principles promote access to key quantum infrastructures by encouraging open access to cloud-based quantum computers, open quantum interoperability standards and protocols, and open-source quantum development tools.

The insight that *safeguarding* can at times be better achieved by *advancing* QT instead of merely seeking to optimize safety alone offers another illustration of the productive dynamics among the principles. In the case of cybersecurity, for instance, advancing quantum computing and quantum cryptography can help accomplish safeguarding objectives by developing new cryptographic protocols that are resistant to quantum attacks. Similarly, by promoting open access to key quantum infrastructures and encouraging the creation of novel hardware, algorithms, and software solutions, one can increase economic growth and competitiveness while also managing the downside risks associated with dominant players achieving monopolistic competitive advantage by restricting access to essential quantum infrastructure.

These interactions among principles apply beyond the corporate competitive dynamics. At the global geopolitical level, an *advancing* QT strategy to ensure overall technological leadership in QT is crucial to achieving the underlying *safeguarding* objectives. Conversely, without *safeguarding* QT advances with appropriate *dual-use* export controls [22, 40] and IP rights, the benefits of such R&D investments and resulting QT innovations could end up accruing to geopolitical adversaries.

## 6. A Path Forward

Quantum technology (QT) roadmaps developed by governments, companies, and consulting firms worldwide anticipate various opportunities, challenges, and risks arising within the next 25 years. Some challenges demand immediate attention, such as establishing practical solutions to protect privacy [18] and ensure information security [19] in light of quantum computing’s threat to widely used public key cryptosystems.<sup>2</sup> Other ethical, legal, social, and political implications of QT may emerge in the longer term, but proactive measures are necessary to guarantee responsible quantum research and development (R&D). Previous cycles of technological innovation – including currently AI – teach us that important ELSPI implications that can emerge in the longer term.

<sup>2</sup> This is now required by President Biden’s executive order on quantum computing [39].

The ten Quantum SEA-principles proposed in this article aim to promote responsible quantum R&D by embedding shared principles and values into the policies and practices of quantum innovators and stakeholders. These principles are interoperable with shared responsible research and innovation (RRI) values [34] while addressing the unique nature of QT. Our interdisciplinary effort seeks to steer the development and use of QT in a direction that aligns with a values-based society and contributes to addressing society's most pressing needs and goals.

The Quantum SEA-Principles are intended to be complementary to existing frameworks for Responsible 4IR Technology, such as the IEEE Ethically Aligned Design Principles, the Asilomar AI Principles, FAIR Data, the Trustworthy AI paradigm, and the WHO guidance on the ethical use of Health AI. Moreover, these principles are designed to apply to technological synergies such as quantum-classical interactions and quantum-AI hybrids. However, since most of QT's ramifications remain unknown, we must approach the implementation of these principles with caution, continuously evaluating and updating them based on our collective experiences.

Looking into the future, responsible quantum innovation principles informed by ELSPI considerations can inform debates on how to regulate QT. This complex and challenging task should be taken on before the technology becomes locked-in and entrenched [5,14]. Crucially, such a regulatory framework must take into account the unique and counter-intuitive properties of applied quantum phenomena, their dual-use nature, and the need to balance open innovation, fair competition [2,36], value appropriation, and risk management [12]. As with other domains such as genomics, it is essential that Quantum-ELSPI work be funded alongside and ideally integrated into opportunities for research funding in QT. In the long run, we anticipate the emergence of a legal and infrastructural ecosystem that includes both horizontal and industry-specific frameworks, such as a Quantum Governance Act or Global Quantum Treaty. Although self-regulation is not enough within the context of QT given its expected power ramifications, soft law instruments based on existing quantum use cases could supplement robust legal frameworks. In a risk-based regulatory environment, standardization, certification, benchmarking, quantum QMS, and life cycle auditing will play a crucial role in promoting sustainable innovation while putting targeted controls and guardrails in place [16].

Further development and operationalization of the guiding principles proposed in this article will require engagement and collaboration among multidisciplinary teams of diverse quantum stakeholders across academia, industry, government, and international organizations. Given the uncertainty

surrounding QT's consequences and societal impact, it is essential for researchers, innovators, and regulators to design methods for contextualizing and implementing agreed-upon principles for responsible quantum innovation and document their application at the level of use cases. The worthy objective of such an ambitious effort is to safeguard, engage, and advance humanity in the quantum age through responsible quantum innovation.

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