Establishing a Legal-Ethical Framework for Quantum Technology


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Abstract
Quantum technologies are rapidly evolving from hypothetical ideas to commercial realities. As the world prepares for these tangible applications, the quantum community issued an urgent call for action to design solutions that can balance their transformational impact. An important first step to encourage the debate is raising quantum awareness. We have to put controls in place that address identified risks and incentivise sustainable innovation. Establishing a culturally sensitive legal-ethical framework for applied quantum technologies can help to accomplish these goals. This framework can be built on existing rules and requirements for AI. We can enrich this framework further by integrating ethical, legal and social issues (ELSI) associated with nanotechnology. In addition, the unique physical characteristics of quantum mechanics demand universal guiding principles of responsible, human-centered quantum technology. To this end, the article proposes ten guiding principles for the development and application of quantum technology. Lastly, how can we monitor and validate that real world quantum tech-driven implementations remain legal, ethical, social and technically robust during their life cycle? Developing concrete tools that address these challenges might be the answer. Raising quantum awareness can be accomplished by discussing a legal-ethical framework and by utilizing risk-based technology impact assessment tools in the form of best practices and moral guides.

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Introduction
Quantum technologies are rapidly evolving from hypothetical ideas to commercial realities. As the world prepares for its tangible applications (such as quantum computing, quantum chemistry, quantum cryptography and the quantum internet), the quantum community issued an urgent call for action to design solutions that can balance their transformational impact.\(^2\)

Raising quantum awareness
An important first step to encourage the debate is raising quantum awareness. The general public has to be taught about quantum technology. People should understand what this key enabling technology can and cannot do. Awareness of its game-changing potential for good, as well as its existential risks, should be raised among scientists, businesses and government. To make informed decisions, policy makers need to wake up today and get ready for quantum.\(^3\)

Next, we have to put controls in place that address identified risks and incentivise sustainable innovation.\(^4\) To ensure societal benefits will be maximized while mitigating adverse effects, crucial work must be done in the areas of quantum ethics, regulation and standardization.\(^5\) Establishing a culturally sensitive legal-ethical framework for applied quantum technologies can help to accomplish these goals.\(^6\)

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\(^6\) Mauritz Kop, Regulating Transformative Technology in The Quantum Age: Intellectual Property, Standardization & Sustainable Innovation, 2 TTLF Newsletter on Transatlantic Antitrust and IPR Developments Stanford-Vienna Transatlantic Technology Law Forum, Stanford University 2020,
What is quantum technology?

Quantum technology is founded on general principles of quantum mechanics and combines the counterintuitive physics of the very small with engineering. Particles and energy at the smallest scale do not follow the same rules as the objects we can detect around us in our everyday lives. The general principles, or properties, of quantum mechanics are superposition, entanglement, and tunnelling. Quantum mechanics aims to clarify the relationship between matter and energy, and it describes the building blocks of atoms at the subatomic level. It describes quantum-scale particles such as protons, neutrons and electrons (fermions), as well as photons, phonons, mesons, gluons and gravitons (bosons). The fundamental theory of quantum mechanics predicts how the microscopic world affects the macroscopic and astronomical one. Einstein’s general theory of relativity, on the other hand, defines the nature of laws of physics on a macro level, including Newton’s gravity, time, space, speed of light, mass and energy (E = mc²).

Einstein’s general relativity theory and quantum mechanics collide in many ways. Gravity is the most fundamental one. String theory attempts to integrate general relativity and quantum mechanics into a theoretical physics paradigm that depicts the behavior of nature’s forces and matter across the universe in one mathematical model. M-theory unifies all versions of String theory.

Finally, constructor theory endeavours to create a new language for physics in which questions about the characteristics of information can be made precise and fully answered. It offers different modes of explanation of our fundamental laws in order to

https://www.sciencedirect.com/science/article/pii/B0125126662001309


https://youtu.be/8DH2xwIYuT0


https://youtu.be/8DH2xwIYuT0


https://www.princeton.edu/physics/faculty/Ismael/constructor-theory.html

describe the physical world more accurately. Constructor theory proposes laws that are scale independent in the sense that these laws are intended to apply to physical systems irrespective of their size. Further, the proposed laws are meant to apply to physical systems regardless of the details of the laws of motion that these systems obey.16

An emerging interdisciplinary research field related to quantum technology that combines the study of information science with quantum effects in physics, is quantum information science (QIS).17 The purpose of QIS is to utilize the properties of nature at the subatomic level to create useful applications, such as quantum computers.18

The quantum computer

We can distinguish six key application areas, or domains, of quantum technology:19

1. Quantum computing
2. Quantum communication
3. Quantum sensing
4. Quantum simulation
5. Fundamental quantum science
6. Artificial intelligence

There are few tangible applications of quantum technology that appeal to the imagination quite as much as the quantum computer. Quantum computing integrates physics, mathematics and computer science.20 Various quantum computing techniques exist today, of which superconducting qubit implementations, trapped ions and light based, photonic boson sampling implementations are particularly promising.21 These machines generally contain various layers of hardware and software components, such as qubits, quantum gates, quantum circuits, quantum algorithms and the quantum-classical interface.22

16 See New directions in Constructor Theory and the foundations of physics (with Chiara Marletto and Vlatko Vedral), Dec 20, 2018, https://www.youtube.com/watch?v=mygaUgDDChC
19 For a further elaboration of quantum technology application areas, see Kop, supra note 6. Each quantum domain has its own separate line of development. In certain cases, the domains intersect.
21 See Daniel Garisto, Light-Based Quantum Computer Exceeds Fastest Classical Supercomputers, Scientific American, Dec 3, 2020, https://www.scientificamerican.com/article/light-based-quantum-computer-exceeds-fastest-classical-supercomputers/. Instead of silicon processors, a setup of lasers, mirrors, prisms and photon detectors was used to solve computational problems. In photonic boson sampling quantum computers, the photons are the qubits.
Qubits are the quantum version of classic bits. A qubit can be a 1 or a 0, or both at the same time. This is called superposition. Qubits can also spin. In addition, quantum particles can be in several places at once, while they remain "aware" of one another. This is known as entanglement. Lastly, quantum tunnelling refers to the phenomenon in which quantum scale particles penetrate a potential energy barrier, such as a brick wall, that is higher in energy. This behavior violates classical mechanics: bigger particles could never achieve this. Quantum scale particles can. Quantum computers depend heavily on these 3 general principles of quantum mechanics.

Quantum computers use special quantum algorithms to do their calculations and simulations. The best-known example is Shor's algorithm, renowned for factoring integers. Shor's algorithm relies on superposition i.e. the capability of a quantum computer to be in multiple states simultaneously.

Stable quantum computers that contain many qubits -regardless of how the qubits actually come about- and that are equipped with robust fault tolerance implementation and quantum error correction mechanisms, are able to outperform the fastest classical Von Neumann architecture exascale supercomputers at specific tasks. This is referred to as quantum supremacy, quantum advantage or quantum primacy.

Quantum computers have a myriad of applications, that open a wealth of opportunities. In general, quantum systems excel in solving complex mathematical optimization problems such as prime factoring, cybersecurity & cryptography and package delivery route optimization. They can also be used to simulate the behaviour of atoms and elementary particles, and to model nature, including weather forecasting. Further, quantum computers are ideally suited for discovering novel (quantum) materials such as next generation batteries and high-performance flat optics, and for developing new lifesaving drugs.

In the coming decades, synergies of quantum technology and AI will provide a new horizon of science to the world. Some predict that quantum computing will play a major role in the rise of autonomous artificial beings and in the creation of Artificial Super Intelligence (ASI). Fourth Industrial Revolution (4IR) key technologies, they believe, will eventually generate an intelligence explosion, unbounded by biological factors such as


25 See, e.g., Fu, supra note 22


27 A. Montanaro, Quantum algorithms: an overview, npj Quantum Inf 2, 15023, 2016, https://doi.org/10.1038/npjqi.2015.23


29 See Andris Ambainis, What Can We Do with a Quantum Computer? How quantum information could lead to a better understanding of the principles of all quantum systems, IAS, 2014, https://www.ias.edu/ideas/2014/ambainis-quantum-computing

30 Quantum computing + machine learning + parallel algorithms = AI on steroids.
...those with which humans of flesh and blood are born. The socio-economic impact of the 4IR will be so far-reaching that we cannot even begin to imagine its consequences.\footnote{For further reading about the predictability of emerging technology, and related policy dilemma’s, see Audley Genus & Andy Stirling, Collingridge and the dilemma of control: Towards responsible and account able innovation, Research Policy, Volume 47, Issue 1, 2018, Pages 61-69, ISSN 0048-7333, \url{https://doi.org/10.1016/j.respol.2017.09.012}.}

From this it follows that we must put controls in place while we still can.

**Connecting AI to quantum**

A legal-ethical framework for quantum technology should build on existing rules and requirements for AI.\footnote{Insofar these rules exist at present: a legal-ethical framework for AI & data is still work in progress in most parts of the world, although the contours of such a framework are becoming more and more manifest.} We should connect AI to quantum.

It is logical to link AI ethics to quantum ethics for two reasons. First of all, much research has already been conducted in this area in recent years. We can build on consensus on ethical codes that has been previously reached. We can stand on the shoulders of the Asilomar principles,\footnote{Asilomar AI Principles, Future of Life Institute, 2017, \url{https://futureoflife.org/ai-principles/}.} the Harvard Berkman Klein Center AI ethics mapping\footnote{Jessica Fjeld et al., Principled Artificial Intelligence: Mapping Consensus in Ethical and Rights-Based Approaches to Principles for AI, Berkman Klein Center Research Publication No. 2020-1, Jan 15, 2020, \url{https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3518482}.} and the EU trustworthy AI paradigm.\footnote{See Ethics guidelines for trustworthy AI, European Commission, Apr 8, 2019, \url{https://ec.europa.eu/digital-single-market/en/news/ethics-guidelines-trustworthy-AI}.} Second: typically, the components of quantum systems are equipped with artificial intelligence. For example, the binary and quantum software interface employs machine learning and neural network technology.\footnote{Such as Quil, see Quantum Computing in 200 Seconds, Rigetti Computing, Feb 24, 2020, \url{https://www.youtube.com/watch?v=z9Izfm4FnP8&feature=emb_logo}.} In other words, these machines essentially are quantum/AI hybrids.

Elsewhere I wrote that countries should adopt a holistic set of ten horizontal core quantum technology rules, or guiding principles, that apply across all industries.\footnote{As for example, the unique physical characteristics of quantum mechanics demand for an extra set of universal guiding principles of responsible, human-centered quantum technology. Core quantum rules should be methodically linked to other areas of the legal system and embedded in existing regulatory structures.} The horizontal guiding principles can be construed

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\footnotetext[31]{For further reading about the predictability of emerging technology, and related policy dilemma’s, see Audley Genus & Andy Stirling, Collingridge and the dilemma of control: Towards responsible and accountable innovation, Research Policy, Volume 47, Issue 1, 2018, Pages 61-69, ISSN 0048-7333, \url{https://doi.org/10.1016/j.respol.2017.09.012}.}

\footnotetext[32]{Insofar these rules exist at present: a legal-ethical framework for AI & data is still work in progress in most parts of the world, although the contours of such a framework are becoming more and more manifest.}

\footnotetext[33]{Asilomar AI Principles, Future of Life Institute, 2017, \url{https://futureoflife.org/ai-principles/}.}


\footnotetext[36]{Such as Quil, see Quantum Computing in 200 Seconds, Rigetti Computing, Feb 24, 2020, \url{https://www.youtube.com/watch?v=z9Izfm4FnP8&feature=emb_logo}. For further reading on quantum computing hardware platforms and standardisation of application programming interfaces (APIs) such as Qatalist, see Michael Vizard, QCI rises to the quantum computing portability challenge, VentureBeat, Feb 17, 2021, \url{https://venturebeat.com/2021/02/17/qci-rises-to-the-quantum-computing-portability-challenge/}.}

\footnotetext[37]{Kop, supra note 6}

\footnotetext[38]{Peebles, supra note 8}

\footnotetext[39]{Cf. Wolfgang Hoffmann-Riem, Artificial Intelligence as a Challenge for Law and Regulation, in Regulating Artificial Intelligence, Editors: Wischmeyer, Thomas, Rademacher, Timo (Eds.), Springer, 2020, 10.1007/978-3-030-32361-5_1. Core quantum principles should function in an efficient manner at the intersection of law and technology and respect International Treaties.}
around public values such as Liberty, Fairness, Dignity, Safety, Security, Sustainability, Privacy, Trust, Equal Access and Net Neutrality.40

Drawing inspiration from nanoethics
We can enrich the envisaged framework further by integrating ethical, legal and social issues (ELSI)41 associated with nanotechnology.42 In other words, we should add nanoethics to the mix.

Nanotechnology is the science of the very small. Nano science and quantum science often intersect while exploring novel physics phenomena.43 Since quantum technology takes us one step further down on the micro scale it is logical to draw inspiration from nanoethics. At the nanoscale, quantum effects are unavoidable and naturally become available. As is the case with AI, much valuable research has already been conducted to identify and map benefits and risks of nanotechnology, including its ethical aspects.44 Moreover, experience has been gained with the application of nanoethical principles in practice.45 We can use the achieved insights and lessons learned to good advantage.

Law and ethics frequently interrelate. Ethical standards should however be a supplementation to legal measures, and not a replacement.46 Ethics alone can never be enough when regulating high-risk technologies.

Ten guiding principles for quantum technology
Let us try to agree on ten overarching principles, or commandments, that protect our democratic values, human rights and fundamental freedoms in the Information Age.47 Allow me—to break the ice—to propose ten guiding principles for the development and application of quantum technology.48 These are meant to raise quantum awareness and encourage the debate. The ground rules aim to put controls in place and integrate our

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41 ELSI in the US, and ELSA in the EU are synonyms.
47 Kop, supra note 6
48 These 10 guiding principles are meant to raise quantum awareness and to encourage the debate.
common democratic norms, standards and values into the design of our future hi-tech systems as much as possible.\textsuperscript{49}

\textit{Principle 1:} We do not violate human rights, including human dignity, human agency, human oversight, the right to an explanation, and the rights of humans with respect to machines.

\textit{Principle 2:} We respect fundamental human freedoms, including human autonomy and liberty.

\textit{Principle 3:} We investigate, develop and design quantum technology systems, including its synergies with other emerging tech such as AI, nanotechnology, blockchain and VR in accordance with human rights, fundamental freedoms, democratic norms, ethical standards and universal, culturally sensitive moral values.

\textit{Principle 4:} We contribute to fairness, transparency, equal opportunities, shared benefit, non-discrimination, diversity, solidarity and prosperity. This includes implementing and safeguarding net neutrality, avoiding power asymmetries, and providing equal service and access to the quantum internet in a democratic society.

\textit{Principle 5:} We respect the process and outcome of democratic decision making. This includes educating the general public on quantum mechanics and related technologies.

\textit{Principle 6:} We apply quantum technology in a responsible, accountable manner, pursuant to the principles of due process and the rule of law.

\textit{Principle 7:} We guarantee technological robustness through standards, benchmarks, audits and certification, that warrant the safety, (mental and physical) security and integrity of people.

\textit{Principle 8:} We comply with laws and regulations on data protection, data governance and privacy.

\textit{Principle 9:} We apply quantum technology in a social, sustainable manner and prevent harmful impact on the environment, society and humanity.

\textit{Principle 10:} We do not create, trade or export quantum applications that violate any of the Principles. This includes disallowing usages that pose existential risks to humanity, such as recursive self-improving systems. We prohibit a quantum arms race by law to avoid self-destruction.

It will be a great challenge to apply these ten principles fairly and globally. Countries like China are clearly now leaders in the field and the rules, habitus and funding systems are very different there.

These horizontal rules should be supplemented with a vertical, differentiated industry-specific legislative approach vis-à-vis sustainable innovation incentives (in line with the innovation policy pluralism toolkit) and risks (based on the pyramid of criticality, which should contain a classification of low, mid and high-risk quantum technology applications, including a mapping of the risks).

The ten most pressing societal risks identified to date are:

1. Risks of increased inequality, monopolization through IP, winner-takes-all effects, and a “quantum divide” during the introductory phase. This holds for both companies and countries.
2. Risks affecting the stability of the economic and financial system, including blockchain and cryptocurrency protocols.
3. Risks concerning data privacy, data security, legal certainty and trust.
4. Risks of fake news, filter bubbles, disinformation and their impact on democratic processes.
5. Risks pertaining to hacking and misuse of encryption and imaging technologies.
6. Risks involving criminal activity such as terrorism, organised crime and tax evasion.
7. Risks of environmental damage.
8. Risks associated with authoritarianism, state surveillance and control.
9. Risks of distorted geopolitical relations, quantum arms races, cyber warfare and altered power constellations.
10. Risks pertaining to human extinction scenarios.

A lack of policy, inaction and absence of international consensus will amplify these risks.

Relatedly, quantum applications listed as dual use items, in the sense that these can be used for good and for evil, should be put under strict trade & export controls in case the risks exceed the benefits. For example, cryptographic dual use items such as quantum-resistant asymmetric algorithms designed for connected civil industry application, could be exploited for military purposes as well. A key objective of export controls is to prevent the proliferation of weapons of mass destruction.

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51 Cf. Kop, supra note 6


55 See, e.g., *Dual-use trade controls*, European Commission,
This horizontal-vertical legal framework should be able to provide clarity about the rules, requirements and responsibilities in light of applied quantum technology such as ownership, legal agenthood, liability, indemnification, insurance and damages, ideally per industry. Naturally, sector-specific regulations for high-risk industries such as health, energy, finance and defense ought to be stricter than the rules for lower risk areas such as the recreation, entertainment, sports, and tourism industries. These regulations should be cohesive and respect the principles of proportionality and subsidiarity.

I envisage an agile, people-oriented legislative system, based on technology roadmapping methods, that can adapt swiftly to changing circumstances and societal needs. Normative preferences about how the Law & Ethics of Quantum should be are dynamic, contextual and culturally sensitive, as society is in constant flux. This means that regulating quantum technology will be a continuous effort that follows the ontogenesis (evolution) of its applications and implementations. Inevitably, the envisioned agile legislative system shall need to be modernized at regular intervals.

Quantum Technology Impact Assessment (QIA)

How can we monitor and validate that real world quantum tech-driven implementations remain legal, ethical, social and technically robust during their life cycle?

Developing concrete tools that address these challenges might be the answer. Instruments such as the Quantum Technology Impact Assessment (QIA) offer entrepreneurs, scientists, programmers and government an 8-step roadmap, and an ex ante code of conduct with which quantum tech can be safely and responsibly implemented in their products and services. They can be a driving force to operationalize the guiding principles in business. The idea behind the QIA is to some extent akin to the work of the former US Office of Technology Assessment (OTA).

The QIA builds on the AI Impact Assessment (the AIIA was the result of a public-private endeavour) and provides a similar moral compass plus risk-based guide. The QIA can

See Kop, supra note 6
See Kop, supra note 46.
Policy makers should be ambitious in exploring new regulatory models, learn from past miscalculations and experiment with responsive solutions.
be used to assess intended effects and unintended consequences of the introduction of quantum technology on the short and longer term.⁶⁴ The central idea behind this concept is that the encompassed best practices can be used to embed our common democratic norms, standards, principles and Humanist, philanthropic values into the architecture of quantum infused systems.⁶⁵ From an incentive-reward perspective, solid quantum-ethical compliance strategies have substantial competitive benefits.

Implementing the QIA in one’s workflow can be done via an internal or an external audit, performed by a specialized, multidisciplinary team. These teams ideally consist of a quantum scientist, an AI developer, a software programmer, a data scientist, a legal counsel, an IP lawyer, a privacy officer, an ethicist, a sociologist, a manager, and an industry specific skilled professional, such as a doctor.

Below are five examples of behavioral rules of practice for quantum systems & applications, that are part of the QIA and the Code of Conduct.⁶⁶ These rules of practise can be extended—depending on the scenario and the application—as desired, and can be used as a roadmap in tandem with the ten proposed core ethical guidelines.

1. Taking care of the integrity of quantum systems, stored information and transfer thereof, and audit the information processing by quantum systems.
2. Ensuring traceability, testability and predictability of the quantum system’s actions.
3. Respecting, not infringing, third party intellectual property rights.
4. Respecting people’s privacy, confidentiality of information, the core ethical guidelines and the sector-specific laws and regulations of the quantum application.
5. Clarifying and delineating responsibilities in the development-components-application-service provider chain.

Sector-specific implementations

Working with sector-specific QIA implementations, or blueprints, is essential.⁶⁷ Industry-specific habits and regulations make it necessary to demarcate. Likewise, the QIA blueprints should cover both US federal and US state level requirements.

For instance, at present, an AI-quantum hybrid in the food sector simply has to comply with the (basic) sector-specific rules of general food law. The same applies to finance, health, sustainable chemistry and transportation. AI and quantum can mainly function here as means to an end. The sectors mentioned are pre-eminently regulated by quality

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conducted. The ECP AI Impact Assessment V1 was written by Kees Stuurman, Bart Schermer, Daniël Frijters and Jelle Attema. See also HLEG’s Assessment List for Trustworthy Artificial Intelligence (ALTAI) for self-assessment, supra note 49; and Recommendations on the human rights impacts of algorithmic systems, Council of Europe, Apr 8, 2020, [https://search.coe.int/cm/pages/result_details.aspx?objectid=09000016809e1154](https://search.coe.int/cm/pages/result_details.aspx?objectid=09000016809e1154).


⁶⁵ In a similar vein, see Nick Bostrom, Ethical Issues in Advanced Artificial Intelligence, 2003, [https://www.nickbostrom.com/ethics/ai.html](https://www.nickbostrom.com/ethics/ai.html)

⁶⁶ These rules of practise are based on the AIIA’s Code of Conduct, and applied to quantum technology, see Kees Stuurman et al., Artificial Intelligence Impact Assessment, ECP, 2019, [https://airecht.nl/s/Artificial-Intelligence-Impact-Assessment-English.pdf](https://airecht.nl/s/Artificial-Intelligence-Impact-Assessment-English.pdf)

management systems (QMS).⁶⁸ So an QIA audit will also have to zoom in on how AI-quantum fits within the context of existing QMS.

From a legal point of view, the economic sectors, or industries, where quantum technology is deployed generally determine the vertical, industry-specific regulations that apply. Such as the FDA safety rules set forth in the Food, Drug, and Cosmetic Act (FD&C Act) pertaining to the pharmaceutical sector and the food industry.⁶⁹ Sectors and industries are a key point of departure for the applicability of product liability regimes, and for proprietary or third-party IP rights.⁷⁰ This is why QIA implementations that are tailored to sectors make sense.

Quantum use cases
Real world quantum use cases are starting to have impact in finance, cryptography, chemistry, traffic engineering, space exploration and more.⁷¹ Applications include the quantum internet, cloud computing, machine learning, machine programming, pattern recognition, mission planning and scheduling, distributed navigation and coordination, system diagnostics, anomaly detection, fault diagnosis and automatic debugging.⁷²

The effects of these use cases on society should be systematically examined and balanced. Cross-disciplinary social-legal-ethical AI & quantum impact assessments with integrated moral compasses should become proactive tools of choice. In practice, this methodology can prevent tampering with the human genome, extending human longevity and creating X-men through recombinant DNA techniques in the health & pharma sector.⁷³ Similarly, risk-based guides could lead to the decision not to develop and manufacture certain quantum applications at all, due to their anthropogenic risks. Applications comparable to the atomic bomb. As a final, more positive example, the QIA is able to take away legal-ethical hurdles when creating new materials that solve environmental problems in the chemical and energy industries. Following this path, technology can assist us in finding solutions to the big questions, such as withering natural resources and climate change.

Intellectual property
Note that assessments can also help to discover what’s needed on the intellectual property (IP) side. On one hand, these can be used to maximize the value of the IP portfolio of the company or the university. Clever tools can assist in recognizing potential IP loopholes and reveal options to register IP. On the other, the need for clearances & third-party licenses can be determined. Additionally, best practices can raise awareness

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⁷⁰ Kop, supra note 6
⁷¹ See, e.g., NASA Quantum Artificial Intelligence Laboratory (QuAIL), NASA, https://hi.arc.nasa.gov/tech/dash/groups/quail/
⁷² See in this context: Neuromorphic, quantum computing and more: Intel labs vision of the future at CES 2021, Endgadget, Jan 12, 2012, https://www.youtube.com/watch?v=qkzlXmAoGNA
about democratizing access to machine learning data and essential quantum technology.74

Quantum ‘Made in USA’
The possibility of combining a successful QIA audit with formal certification, comparable to a ‘USA Compliance’ conformity marking or a ‘Quantum Made in USA’ accreditation, indicating it has met safety, health and environmental protection standards for the region, should be explored.75 Note that certification (and perhaps even market authorization) should rather not be granted by private parties with commercial objectives, but by independent public oversight bodies such as the FDA.76 The benefits are two-fold: besides addressing risks and threats to humanity, this approach is capable to play a key role in providing guarantees, confidence and trust, and in removing perceived barriers for quantum start-ups to flourish.77 Technology that gained the trust of the general public has significant marketing advantages.78

Moreover, regulating new technologies can be a lengthy process. It is expected that a future framework for quantum technology will eventually consist of binding and non-binding legal instruments, accompanied by various types of compliance and enforcement mechanisms.79 Mechanisms such as certification, quality labelling, audits and regulatory sandboxes. In the event that regulation in the form of binding, overarching legal-ethical frameworks turns out to be an unrealistic option80, values-based technology assessment tools can be used as soft law alternatives for insufficient or non-existent legislation.81

How can we encourage the debate in concrete terms?
The uncharted cross-disciplinary field of Quantum-ELSI (ethical, legal, social implications)82 represents a rare chance to establish a harmonized groundwork of globally pursued, common principles. The most effective time to think through the ethical, legal and social implications of a technology is when that technology is still in its infancy,

74 Cf. Kop, supra note 59
81 Leaving (self-)regulation entirely to the industry is not a good option, especially in hi-risk areas. Companies simply have different motives than the state as regards promoting the public good.
as there is still room for early intervention. At a later stage, room to steer things into the right direction will be gone, partly as a result of path dependence.\textsuperscript{83}

Global collaboration on this matter is strongly preferred.\textsuperscript{84} Unfortunately, it is not inconceivable that the development and uptake of macro-level, transnational quantum principles will run along the lines of democratic and authoritarian tech governance models. This could eventually result in separate tech blocks, or international values-based partnerships between countries with shared digital DNA, that each have their own quantum platforms and apps.\textsuperscript{85}

Quantum-ELSI and the Responsible Research and Innovation (RRI) approach intend to proactively anticipate the societal impact of scientific research, and focus on building bridges between stakeholders, research communities and the general public.\textsuperscript{86} Both ELSI and the RRI practices can be applied to quantum technology, and help ensure that the outcomes from research and development are beneficial and acceptable to society.\textsuperscript{87}

Who should play an active role?

First, academia. Organizing interdisciplinary conferences that put these issues on the agenda would be a good step to initiate the quantum debate. For this, it is important that the right questions are formulated.\textsuperscript{88} Questions about who should control the development, about monopolizing or democratizing quantum technology, on what level of control should be maintained, and regarding researchers actively anticipating social, political, and ethical consequences of their work, including principles of diversity.\textsuperscript{89} In general, researchers have the duty to take responsible research and innovation more seriously.\textsuperscript{90} Risks, legal gaps, ethical questions, societal implications and other unknown impacts associated with quantum computing should be studied.\textsuperscript{91} Sociologists and anthropologists have to describe the role quantum can play in social and cultural interactions and what possible consequences this can have for life on earth and


\textsuperscript{85} See, e.g., Mauritz Kop, Democratic Countries Should Form a Strategic Tech Alliance, 1 TTLF Newsletter on Transatlantic Antitrust and IPR Developments Stanford-Vienna Transatlantic Technology Law Forum, Stanford University 2021, Forthcoming.


\textsuperscript{87} For an example of a public dialogue on Quantum Technologies based on RRI principle, see \textit{Will quantum computing make the world better?}, Inspired Research, Oxford University, Department of Computer Science, 2018, https://www.cs.ox.ac.uk/innovation/research-impact/case-quantum-better-world.html; see also Bernd Stahl & Catherine Flick, \textit{ETICA Workshop on Computer Ethics: Exploring Normative Issues}, IFIP Advances in Information and Communication Technology, 2011, 352. 64-77. 10.1007/978-3-642-20769-3_6.


\textsuperscript{89} See, e.g., Catherine N. Steffel, \textit{Shaping the technology transforming our society}, Fermilab, Dec 12, 2019, https://news.fnal.gov/2019/12/shaping-the-technology-transforming-our-society/

\textsuperscript{90} Quantum Technologies Public Dialogue Report, supra note 52

relationships between people. Insights should be shared. Best practices should be designed, exchanged and tested in real world use cases by the expert community.  

Ultimately, it is crucial that interdisciplinary research groups produce normative outputs in the quantum ethics domain. Agreed on benchmarks, laid down in tools such as quantum impact assessments, should be able to measure the effects of implemented quantum-related ethics guidelines on the development of the technology and its applications.  

Second, governments must encourage golden triangle public-private partnerships that co-operate on the challenges surrounding quantum technology. On the local, national and international levels. These partnerships should collaborate across disciplines and institutions, committed to creating a better world. Governments should bring the quantum community together, organize multi-stakeholder debates in preparation for governance, set time paths and issue calls to action to design both technical and regulatory control mechanisms. The authorities should answer questions concerning restricting public access to certain applications, in scenarios where the risks of public access outweigh societal benefits. Governments should use systematic technology assessment methods to forecast future trends of quantum technology evolution. Ultimately, governments should set up quantum-targeted strategies and policies to maximize the promise of the technology.  

Further, governments should make sure that the workforce is trained for quantum as soon as possible, across industries. Roadblocks for SMEs should be removed. The government must invest urgently and heavily in education and build bridges between disciplines. Quantum literacy should be encouraged on government and leadership levels. Cross-disciplinary high school, college and university curricula should integrate applied quantum science in courses like physics, chemistry, computer science, social studies, humanities, health sciences, economy and law. The general public should be taught and informed by launching media editorials and campaigns. With the goal of taking away anxiety of the unknown, becoming more aware of risks and engaged and excited by potential benefits associated with quantum technology. Specialized institutions that provide guidance, legal certainty, guarantees and trust on the current possibilities with regard to the development and use of quantum technology should be established.  

Third, companies should engage in a dialogue about constructing a meaningful quantum business ethos and explore the creation of sustainable quantum value chains. Enablers and obstacles for scalable quantum solutions should be examined. Companies should implement technology impact assessments and codes of conduct that prioritize, monitor and validate the safe and responsible application of quantum technology in their products and services.

92 id.
94 For an example of technical control mechanisms, see Trent McConaghy, How Blockchains could transform Artificial Intelligence, DataConomy, Dec 21, 2016, https://dataconomy.com/2016/12/blockchains-for-artificial-intelligence/
95 Quantum Technologies Public Dialogue Report, supra note 52
96 See Liu, Jianhua & Guo, Ying & Porter, Alan & Huang, Ying, supra note 62.
97 id.
98 Cf. Kop, supra note 46 and 59
Conclusion
Quantum physics is quickly materializing into real-world technology. Anticipating spectacular advancements in quantum science, the time is ripe for governments, academia and the market to prepare regulatory strategies that match the power of the technology. Raising quantum awareness can be accomplished by discussing a legal-ethical framework and by utilizing risk-based impact assessment tools in the form of best practices and moral guides.