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.

TABLE OF CONTENTS

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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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[2] *See, e.g.,* The Quantum Daily, *Quantum Ethics | A Call to Action*, Feb 1, 2021, https://thequantumdaily.com/2021/02/01/quantum-ethics-a-call-to-action/; Sara Castellanos, *Quantum Computing Scientists Call for Ethical Guidelines*, The Wall Street Journal, Feb 1, 2021, https://www.wsj.com/articles/quantum-computing-scientists-call-for-ethical-guidelines-11612155660

[3] D.F. Reding & J. Eaton, *NATO Report Science & Technology Trends: 2020-2040*, NATO Science & Technology Organization, March 2020; *NATO report looks at impact of technology on our security*, NATO, May 4, 2020, https://www.nato.int/cps/en/natohq/news_175574.htm

[4] *Cf.* (from an AI helicopter view) Paul Nemitz & Matthias Pfeffer, *Prinzip Mensch. Macht, Freiheit und Demokratie im Zeitalter der Künstlichen Intelligenz*, Dietz Verlag J.H.W. Nachf, Aug 2020, https://prinzipmenscheu.wordpress.com/

[5] The JTC 1 quantum computing standardization program is currently working on global ISO and IEC norms, *see Working Group 14 for Quantum computing was established by ITO/IEC JTC1 in June 2020,* JTC1, https://jtc1info.org/technology/working-groups/quantum-computing/ . Other early stage efforts towards standardisation are: ISO, *ISO/IEC AWI 4879 Information technology — Quantum computing — Terminology and vocabulary,* https://www.iso.org/standard/80432.html; *ISO/IEC JTC 1 Information technology,* ISO, https://www.iso.org/committee/45020.html and *CEN-CENELEC Focus Group on Quantum Technologies,* CEN-CENELEC, https://www.cencenelec.eu/standards/topics/quantumtechnologies/pages/default.aspx

[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.[7] 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).[8] The fundamental theory of quantum mechanics predicts how the microscopic world affects the macroscopic and astronomical one.[9] 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 ($E = mc^2$).[10]

Einstein's general relativity theory and quantum mechanics collide in many ways.[11] Gravity is the most fundamental one.[12] 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.[13] M-theory unifies all versions of String theory.[14]

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.[15] It offers different modes of explanation of our fundamental laws in order to

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https://law.stanford.edu/publications/regulating-transformative-technology-in-the-quantum-age-intellectual-property-standardization-sustainable-innovation/

[7] The resulting mathematical inequalities, mysteries and paradoxes, such as the uncertainty principle, quantum tunnelling, quantum teleportation, quantum randomness and indeterminacy, and the parallel universes/many worlds interpretation of quantum mechanics, are counterintuitive to the human experience. For future generations of people, quantum phenomena that seem implausible and contradict observed reality might become more well-known and familiar.

[8] The general principles of quantum mechanics can be stated both in terms of wave mechanics and in standard abstract linear space formalism, *see* PJE Peebles, *Quantum Mechanics*, Princeton University Press, 12 Apr, 1992, https://press.princeton.edu/books/hardcover/9780691087559/quantum-mechanics; *See also* V. Mastropietro, *Fermionic Systems*, Encyclopedia of Mathematical Physics, Editor(s): Jean-Pierre Françoise, Gregory L. Naber, Tsou Sheung Tsun, Academic Press, 2006, Pages 300-307, ISBN 9780125126663, https://doi.org/10.1016/B0-12-512666-2/00130-9. (https://www.sciencedirect.com/science/article/pii/B0125126662001309)

[9] *See, e.g.,* Ismael, Jenann, *Quantum Mechanics*, The Stanford Encyclopedia of Philosophy (Winter 2020 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/win2020/entries/qm/

[10] Albert Einstein, *On the Electrodynamics of Moving Bodies*, by Annalen der Physik, 17, 1905. Reprinted in *The Principle of Relativity*, Dover Pub. E = Energy, M= Mass, C= Speed of light.

[11] For example, there are a number of phenomena that can only be explained by quantum mechanics (and not by classical physics, nor by general relativity), such as superconductivity and the Meissner effect, entanglement, nonlocality, ferromagnetism and atomic spectral lines. *See The magnet that didn't exist*, QuTech, 2 Mar, 2020, https://qutech.nl/2020/03/02/the-magnet-that-didnt-exist/

[12] M-theory (M stands for Magic or Mystery) attempts to solve the problem of quantum gravity. It is considered by many as the best candidate for a Theory of Everything. *See* Edward Witten, 1995, http://www.math.stonybrook.edu/Videos/IMS/video.php?f=35-Witten

[13] *See, e.g.,* Kevin Wray, *An Introduction to String Theory*, 2009; *see also* Charlie Wood, *What Is String Theory?*, SPACE.com, Jul 11, 2019, https://www.space.com/17594-string-theory.html

[14] Edward Witten, *String Theory Dynamics In Various Dimensions*, 1995, https://arxiv.org/abs/hep-th/9503124

[15] *See* Constructor Theory (with David Deutsch), Apr 4, 2015, https://youtu.be/8DH2xwIYuT0

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]

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[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=myqaUgDDCHc

[17] *See, e.g.,* B. Brecht *et al.*, *Photon Temporal Modes: A Complete Framework for Quantum Information Science*, Phys. Rev. X 5, 041017, Erratum, 30 Oct 2015, Phys. Rev. X 6, 019901 (2016), https://doi.org/10.1103/PhysRevX.5.041017 and *Quantum Information Science - An Emerging Field of Interdisciplinary Research and Education in Science and Engineering, Report of the NSF Workshop October 28-29, 1999 Arlington, Virginia*, NSF, 1999, https://www.nsf.gov/pubs/2000/nsf00101/nsf00101.htm

[18] *See, e.g.,* Aaron Dalton, *Quantum technology comes of age,* Science, Nov 15, 2019, https://www.sciencemag.org/features/2019/11/quantum-technology-comes-age

[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.

[20] *See* Hagar, Amit and Michael Cuffaro, Quantum Computing, *The Stanford Encyclopedia of Philosophy* (Winter 2019 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/win2019/entries/qt-quantcomp/ https://plato.stanford.edu/entries/qt-quantcomp/#Basi

[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.

[22] *See, e.g., 5 Essential Hardware Components of a Quantum Computer*, in *Quantum Computing: Progress and Prospects*, National Academies of Sciences, Engineering, and Medicine, Washington, DC, The National Academies Press, 2019, doi: 10.17226/25196, https://www.nap.edu/read/25196/chapter/7#114

Qubits are the quantum version of classic bits.[23] A qubit can be a 1 or a 0, or both at the same time. This is called superposition. Qubits can also spin.[24] In addition, quantum particles can be in several places at once, while they remain "aware" of one another. This is known as entanglement.[25] 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.[26] 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.[27] The best-known example is Shor's algorithm, renowned for factoring integers.[28] 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.[29] 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.[30] 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

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[23] *See, e.g.,* Xiang Fu, *Quantum Control Architecture: Bridging the Gap between Quantum Software and Hardware*, Delft University of Technology, (2018), https://doi.org/10.4233/uuid:8205cc34-30df-45f0-b6eb-8081bdb765b8.

[24] *See Understanding quantum computing*, Microsoft, 1 Feb 2021, https://docs.microsoft.com/en-us/quantum/overview/understanding-quantum-computing

[25] *See, e.g.,* Fu, *supra* note 22

[26] *See, e.g.,* SJ Ling, *The Quantum Tunnelling of Particles through Potential Barriers*, BCcampus Open Publishing, Jul 23, 2019, https://opentextbc.ca/universityphysicsv3openstax/chapter/the-quantum-tunneling-of-particles-through-potential-barriers/

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

[28] *See Shor's Algorithm*, Qiskit, https://qiskit.org/textbook/ch-algorithms/shor.html

[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.[31]

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.[32] 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,[33] the Harvard Berkman Klein Center AI ethics mapping[34] and the EU trustworthy AI paradigm.[35] 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.[36] 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.[37] In addition to the norms, standards and tenets we embraced for AI, the unique physical characteristics of quantum mechanics[38] 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.[39] The horizontal guiding principles can be construed

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[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, https://doi.org/10.1016/j.respol.2017.09.012, (https://www.sciencedirect.com/science/article/pii/S0048733317301622). For further reading on the expected societal impact of quantum, *see Global Future Council on Quantum Applications*, World Economic Forum, https://www.weforum.org/communities/gfc-on-quantum-applications

[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.

[33] *Asilomar AI Principles*, Future of Life Institute, 2017, https://futureoflife.org/ai-principles/

[34] 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, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3518482

[35] *See* Ethics guidelines for trustworthy AI, European Commission, *Apr 8, 2019*, https://ec.europa.eu/digital-single-market/en/news/ethics-guidelines-trustworthy-AI. Trustworthy AI has 7 key requirements: Human agency and oversight, Technical robustness and safety, Privacy and Data Governance, Transparency, Diversity, Non-discrimination and fairness, Societal and environmental well-being, and Accountability.

[36] Such as Quil, *see Quantum Computing in 200 Seconds*, Rigetti Computing, Feb 24, 2020, https://www.youtube.com/watch?v=z9fZfm4FnP8&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, https://venturebeat.com/2021/02/17/qci-rises-to-the-quantum-computing-portability-challenge/

[37] Kop, *supra* note 6

[38] Peebles, *supra* note 8

[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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[40] *See, e.g., Quantum Internet | The internet's next big step*, TU Delft, Jun 3, 2019, https://issuu.com/tudelft-mediasolutions/docs/quantum_magazine_june_2019 and Pieter E. Vermaas, *The societal impact of the emerging quantum technologies: a renewed urgency to make quantum theory understandable*, Ethics Inf Technol, 2017, https://dl.acm.org/doi/abs/10.1007/s10676-017-9429-1

[41] ELSI in the US, and ELSA in the EU are synonyms.

[42] *See, e.g.,* BL Shumpert et al., *Specificity and Engagement: Increasing ELSI's Relevance to Nano-Scientists*, Nanoethics, 2014, 8(2):193-200, doi:10.1007/s11569-014-0194-x, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4129220/

[43] *See, e.g.,* Mark. L. Brongersma, *The road to atomically thin metasurface optics*, Nanophotonics, 10 (1), 2020, https://doi.org/10.1515/nanoph-2020-0444

[44] *See, e.g.,* Antonio G. Spagnolo, & Viviana Daloiso, *Outlining Ethical Issues in Nanotechnologies,* Bioethics. 23. 394-402, 2009, 10.1111/j.1467-8519.2007.00623.x. and Tsjalling Swierstra et al., *Converging Technologies, Shifting Boundaries,* Nanoethics. 3. 213-216, 2009, 10.1007/s11569-009-0075-x.

[45] *See Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues*, National Research Council and National Academy of Engineering, Washington, DC: The National Academies Press, 2014, https://doi.org/10.17226/18512

[46] *See* Mauritz Kop, *Shaping the Law of AI: Transatlantic Perspectives*, TTLF Working Papers No. 65, Stanford-Vienna Transatlantic Technology Law Forum,2020, https://law.stanford.edu/publications/no-65-shaping-the-law-of-ai-transatlantic-perspectives/

[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:[49]

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.

Principle 2: We respect fundamental human freedoms, including human autonomy and liberty.

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.

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.

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

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

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

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

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

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.

[49] The guiding principles are *inter alia* based on the *European group on ethics in science and new technologies' Statement on artificial intelligence, robotics and autonomous systems*, European Commission, Brussels, 2018, https://op.europa.eu/en/publication-detail/-/publication/dfebe62e-4ce9-11e8-be1d-01aa75ed71a1; the *Assessment List for Trustworthy Artificial Intelligence (ALTAI) for self-assessment*, High-Level Expert Group on Artificial Intelligence (AI HLEG), Brussels, Jul 17,2020, https://ec.europa.eu/digital-single-market/en/news/assessment-list-trustworthy-artificial-intelligence-altai-self-assessment; and the *Asilomar AI Principles*, Future of Life Institute, 2017, https://futureoflife.org/ai-principles/, and applied to quantum technology. *See also* https://airecht.nl/s/Artificial-Intelligence-Impact-Assessment-English.pdf. Eventually,, the ten agreed on commandments should be codified in a Treaty, or Declaration on Guiding Principles for Quantum Technology.

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)[50] 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).[51]

The ten most pressing societal risks identified to date are: [52]

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.[53] 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.[54] A key objective of export controls is to prevent the proliferation of weapons of mass destruction.[55]

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[50] *See* Daniel J. Hemel & Lisa Larrimore Ouellette, *Innovation Policy Pluralism*, 128 YALE L.J. 2019, https://digitalcommons.law.yale.edu/ylj/vol128/iss3/1. Central idea is the layering of traditional and alternative innovation incentive & allocation options such as intellectual property (including flexibilities), prizes, subsidies, fines, benchmarks and competitions, per industry.
[51] *Cf.* Kop, *supra* note 6
[52] *id.*, and *Summary of the Quantum Technologies Public Dialogue Report*, EPSRC, Oxford University 2019, https://webarchive.nationalarchives.gov.uk/20200930161517/https://epsrc.ukri.org/newsevents/pubs/epsrc-quantum-technologies-public-dialogue-summary-report/
[53] *See* in this light: F. Sevini et al., *Emerging dual-use technologies and global supply chain compliance*, IAEA Safeguards Symposium 2018, Vienna, 2018, https://www.researchgate.net/publication/330258872_EMERGING_DUAL-USE_TECHNOLOGIES_AND_GLOBAL_SUPPLY_CHAIN_COMPLIANCE
[54] *See European Commission proposes updates to the EU Dual-Use List and published its latest annual report*, Lexology, Nov 20, 2019, https://www.lexology.com/library/detail.aspx?g=6eef793c-834e-4866-9212-e3c4f30f1bc4
[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.[56] 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,[57] that can adapt swiftly to changing circumstances and societal needs.[58] Normative preferences about how the Law & Ethics of Quantum should be are dynamic, contextual and culturally sensitive, as society is in constant flux.[59] This means that regulating quantum technology will be a continuous effort that follows the ontogenesis (evolution) of its applications and implementations.[60] Inevitably, the envisioned agile legislative system shall need to be modernized at regular intervals.[61]

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).[62]

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.[63] The QIA can

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https://ec.europa.eu/trade/import-and-export-rules/export-from-eu/dual-use-controls/

[56] *See* Kop, *supra* note 6

[57] *See, e.g.,* Stefaan Verhulst, *Introducing the Digital Policy Model Canvas*, The Gov Lab, Sep 22, 2017, http://thegovlab.org/introducing-the-digital-policy-model-canvas/

[58] *See, e.g., White Paper Digital Policy Playbook 2017: Approaches to National Digital Governance*, World Economic Forum, 2017, http://www3.weforum.org/docs/White_Paper_Digital_Policy_Playbook_Approaches_National_Digital_Governance_report_2017.pdf

[59] *See* Mauritz Kop, *The Right to Process Data for Machine Learning Purposes in the EU*, Harvard Law School, Harvard Journal of Law & Technology (JOLT) Online Digest 2021, Forthcoming, https://ssrn.com/abstract=3653537; *see also* Mark P. McKenna, and Christopher Jon Sprigman, *What's In, and What's Out: How IP's Boundary Rules Shape Innovation,* Harvard Journal of Law and Technology, Vol. 30, No. 2, 2017, http://dx.doi.org/10.2139/ssrn.2735073

[60] *See* Kop, *supra* note 46.

[61] Policy makers should be ambitious in exploring new regulatory models, learn from past miscalculations and experiment with responsive solutions.

[62] *See Office of Technology Assessment*, Wikipedia, https://en.wikipedia.org/wiki/Office_of_Technology_Assessment; *see also* Alan L. Porter, *Technology Assessment*, 1995, https://doi.org/10.1080/07349165.1995.9726087 and Jianhua Liu et al., *A systematic method for technology assessment: Illustrated for 'Big Data'*, 2762-2769, PICMET, IEEE, 2016, https://ieeexplore.ieee.org/document/7806836

[63] Mauritz Kop, *AI Impact Assessment & Code of Conduct*, European AI Alliance (European Commission), May 29, 2019, https://futurium.ec.europa.eu/en/european-ai-alliance/best-practices/ai-impact-assessment-code-

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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conduct. 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.

[64] *Cf. Technology Assessment,* IAIA International Association for Impact Assessment, 2009, https://www.iaia.org/wiki-details.php?ID=26

[65] In a similar vein, *see* Nick Bostrom, *Ethical Issues in Advanced Artificial Intelligence,* 2003, 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

[67] For an Overview of trends in the US Quantum Ecosystem, *see* Sean Silbert, *Quantum computing nearing commercial reality*, Netherlands Innovation Network, Jan 12, 2021, https://nlintheusa.com/quantum-computing-nearing-commercial-reality/

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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[68] *See, e.g.,* A. Bolton, *Quality Management Systems for the Food Industry - A guide to ISO 9001/2*, Springer, 1997, https://www.springer.com/gp/book/9781461377900

[69] *See* Mauritz Kop, *Machine learning and EU data-sharing practices: Legal aspects of machine learning training datasets for AI systems*, in Research Handbook on Big Data Law edited by Roland Vogl, Chapter 22, pp. 431-452, Edward Elgar Publishing Ltd., 2021, Forthcoming; and *Federal Food, Drug, and Cosmetic Act (FD&C Act)*, FDA, https://www.fda.gov/regulatory-information/laws-enforced-fda/federal-food-drug-and-cosmetic-act-fdc-act

[70] Kop, *supra* note 6

[71] *See, e.g., NASA Quantum Artificial Intelligence Laboratory (QuAIL),* NASA, https://ti.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

[73] *See* Henry T. Greely, *CRISPR People*, MIT Press Ltd, 2021, https://mitpress.mit.edu/books/crispr-people

about democratising 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 option[80], 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,

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[74] *Cf.* Kop, *supra* note 59

[75] *See US Compliance*, https://www.uscompliance.com/

[76] Mauritz Kop, *AI & Intellectual Property: Towards an Articulated Public Domain*, 28 Tex. Intell. Prop. L. J. 297, 2020, http://tiplj.org/wp-content/uploads/Volumes/v28/Kop_Final.pdf

[77] *Cf.* James Manyika and William H. McRaven, *Chairs,* Adam Segal, *Project Director, Innovation and National Security Keeping Our Edge, Independent Task Force Report No. 77,* Council on Foreign Relations, Sep 2019, https://www.cfr.org/report/keeping-our-edge/

[78] *See, e.g.,* Marietje Schaake & Lisa Witter, *How leaders can use 'agile governance' to drive tech and win trust*, World Economic Forum, Jan 18, 2019, https://www.weforum.org/agenda/2019/01/agile-governance-drive-new-tech-public-trust/

[79] *Cf. The feasibility study on AI legal framework adopted by the CAHAI*, Council of Europe, Dec 17, 2020, https://www.coe.int/en/web/artificial-intelligence/-/the-feasibility-study-on-ai-legal-standards-adopted-by-cahai

[80] *See, e.g.,* Mark A. Lemley, *The Contradictions of Platform Regulation*, Feb 3, 2021, available at SSRN: https://ssrn.com/abstract=3778909

[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.

[82] *See* in this light *also*: J.R. Tuma, *Nanoethics and the breaching of boundaries: a heuristic for going from encouragement to a fuller integration of ethical, legal and social issues and science: commentary on: "Adding to the mix: integrating ELSI into a National Nanoscale Science and Technology Center".* Sci Eng Ethics, Dec;17(4):761-7, Epub, Nov 17, 2011, PMID: 22090342, doi: 10.1007/s11948-011-9322-y

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.[83]

Global collaboration on this matter is strongly preferred.[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.[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.[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.[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.[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.[89] In general, researchers have the duty to take responsible research and innovation more seriously.[90] Risks, legal gaps, ethical questions, societal implications and other unknown impacts associated with quantum computing should be studied.[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

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[83] *See, e.g.,* Caroline Banton, *Path Dependency*, Investopia, Jan 31, 2021, https://www.investopedia.com/terms/p/path-dependency.asp

[84] *See, e.g.,* Dario Gil, *Turbocharging scientific discovery: with bits, neurons, qubits – and collaboration,* World Economic Forum, Aug 7, 2020, https://www.weforum.org/agenda/2020/08/accelerated-discovery-science-materials-quantum-computing-artificial-intelligence-ai-high-performance-computers-hpc-ibm/

[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.

[86] *See, e.g., ELSA: ethical, legal and social aspects*, CORDIS, EU research results, European Commission, Jul 26, 2007, https://cordis.europa.eu/programme/id/FP4-BIOTECH-2_0901

[87] For an example of a public dialogue on Quantum Technologies based on RRI principle, *see 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, *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.

[88] *See, e.g.,* David Deutsch, *The Beginning of Infinity*, Penguin Group Usa, 2011, https://www.thebeginningofinfinity.com/

[89] *See, e.g.,* Catherine N. Steffel, *Shaping the technology transforming our society*, Fermilab, Dec 12, 2019, https://news.fnal.gov/2019/12/shaping-the-technology-transforming-our-society/

[90] Quantum Technologies Public Dialogue Report, *supra* note 52

[91] *See, e.g., Quantum Computing Ethics*, World Economic Forum, 2021, https://www.weforum.org/projects/quantum-computing-ethics

relationships between people. Insights should be shared. Best practices should be designed, exchanged and tested in real world use cases by the expert community.[92]

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.[93]

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.[94] The authorities should answer questions concerning restricting public access to certain applications, in scenarios where the risks of public access outweigh societal benefits.[95] Governments should use systematic technology assessment methods to forecast future trends of quantum technology evolution.[96] 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.[97] 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.[98]

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.

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92 *id.*

93 *See* for the current lack of consensus and benchmarks on AI ethics: *2021 AI Index Report*, HAI, Stanford University, 2021, https://hai.stanford.edu/research/ai-index-2021; *TOOLBOX: Dynamics of AI Principles*, AI Ethics Lab, Dec 2020, https://aiethicslab.com/big-picture/ and *AI Initiatives*, Council of Europe, https://www.coe.int/en/web/artificial-intelligence/national-initiatives

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.