Conditional Futures of Responsible Quantum Technologies

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Summary

Quantum technologies (QT) are an emerging field focused on utilizing quantum mechanical phenomena, particularly entanglement, for innovative applications in computing, communication, and sensing. Although quantum mechanics enabled key technologies such as lasers and transistors, these earlier innovations did not rely on manipulating single quantum systems or entangled states. Beginning notably in the 1990s, physicists, computer scientists, and information theorists proposed second-generation quantum technologies, generating substantial interest due to their implications for cryptographic security and defense.

In 2016, thousands of European quantum researchers signed The Quantum Manifesto to call for a 1 billion € grand initiative, IBM put its first five-qubit quantum processor on the cloud for everyone to access, and China launched the world's first quantum communication satellite. Things have only further escalated since then, leading to a point where 2025 is officially announced as the International Year of Quantum Science and Technology by the UN. These rapid and ongoing developments in QT necessitate careful technology assessment (TA), which seeks to anticipate both intended and unintended consequences of technological advancements. Emerging technologies like QT pose particular challenges for TA because of their high uncertainty, speculative nature, and potentially profound societal impacts. Addressing these challenges early is crucial to identifying critical path dependencies and managing the scope of future problems effectively.

This thesis addresses two central research questions: (i) How can responsible quantum technologies be imagined, envisioned, and realized by the quantum technologies community, and (ii) What are the relevant topics and potential critical path dependencies for responsibly developing these technologies?

Chapter 1 provides an extensive overview of QT, covering commercial, academic, technical, educational, and geopolitical aspects. Chapter 2 investigates how responsibility is conceptualized, discussed, and practiced within the QT community. Chapter 3 synthesizes the findings from earlier chapters, identifying critical conditions and key path dependencies for achieving responsible QT futures. Through this exploratory study, the thesis explicitly contributes to TA by examining QT as a case for understanding and engaging with emerging technologies. It identifies significant conditions shaping QT's development paths, enabling anticipation of technological, ethical, and societal issues. Ultimately aimed at providing further insights for better managing the complexities and uncertainties of emerging technological domains.

Zusammenfassung

Quantentechnologien (QT) sind ein aufstrebendes Forschungsfeld, das sich mit der Nutzung quantenmechanischer Phänomene, insbesondere der Verschränkung, für neuartige Anwendungen in den Bereichen Computing, Kommunikation und Sensorik beschäftigt. Obwohl die Quantenmechanik bereits Schlüsseltechnologien wie Laser und Transistoren ermöglichte, basierten diese früheren Innovationen nicht auf der gezielten Manipulation einzelner Quantensysteme oder verschränkter Zustände. In den 1990er Jahren begannen Physiker, Informatiker und Informationstheoretiker sogenannte Quantentechnologien der zweiten Generation vorzuschlagen, die aufgrund ihrer möglichen Auswirkungen auf kryptografische Sicherheit und Verteidigung großes Interesse weckten.

Im Jahr 2016 unterzeichneten Tausende europäischer Quantenforscher das sogenannte Quantenmanifest, um eine milliardenschwere europäische Großinitiative zu fordern. Im gleichen Jahr stellte IBM seinen ersten Fünf-Qubit-Quantenprozessor der breiten Öffentlichkeit in der Cloud zur Verfügung, und China startete den weltweit ersten Quantenkommunikationssatelliten. Seither hat sich die Dynamik weiter verstärkt, sodass die Vereinten Nationen das Jahr 2025 offiziell zum Internationalen Jahr der Quantenwissenschaft und -technologie erklärten.

Diese rasanten Entwicklungen machen eine sorgfältige Technikfolgenabschätzung (TA) erforderlich, deren Ziel es ist, sowohl beabsichtigte als auch unbeabsichtigte Folgen des technologischen Fortschritts zu antizipieren. Neue und aufkommende Technologien wie QT stellen die TA dabei vor besondere Herausforderungen, da sie durch große Unsicherheiten, spekulative Erwartungen und potenziell tiefgreifende gesellschaftliche Auswirkungen geprägt sind. Die frühzeitige Beschäftigung mit diesen Herausforderungen ist entscheidend, um kritische Pfadabhängigkeiten zu erkennen und künftige Problemhorizonte effektiv zu adressieren.

Die vorliegende Arbeit widmet sich zwei zentralen Forschungsfragen: (i) Wie können verantwortungsvolle Quantentechnologien von der QT-Community imaginiert, entworfen und umgesetzt werden? (ii) Welche Themen und kritischen Pfadabhängigkeiten sind für die verantwortungsvolle Entwicklung dieser Technologien relevant?

Kapitel 1 bietet eine umfassende Bestandsaufnahme der QT und behandelt kommerzielle, akademische, technische, bildungspolitische und geopolitische Aspekte. Kapitel 2 analysiert, wie Verantwortung innerhalb der QT-Community verstanden, diskutiert und praktiziert wird. Kapitel 3 fasst die Erkenntnisse aus den vorangegangenen Kapiteln zusammen und identifiziert zentrale Bedingungen und Pfadabhängigkeiten für verantwortungsvolle QT-Zukünfte.

Mit dieser explorativen Studie trägt die Arbeit explizit zur TA bei, indem sie QT exemplarisch nutzt, um den Umgang mit neuen Technologien besser zu verstehen. Sie identifiziert wesentliche Faktoren, die die Entwicklungspfade von QT prägen, und ermöglicht so die frühzeitige Antizipation technologischer, ethischer und gesellschaftlicher Herausforderungen. Ziel der Arbeit ist es, die TA mit neuen Erkenntnissen für den besseren Umgang mit Unsicherheiten und Komplexitäten in aufkommenden Technologiefeldern zu unterstützen.

List of Abbreviations

A.I.: Artificial Intelligence
BSI: Federal Office for Information Security
CTA: Constructive Technology Assessment
EDA: European Defence Agency
EDI: Equity, Diversity, and Inclusion
EDTs: Emerging and Disruptive Technologies
ENDR: European Network Of Defence-Related Regions
ESG: Environmental, Social, and Governance
EQTC: European Quantum Technologies Conference
EuroQCI: European Quantum Communication Infrastructure
IYQ: International Year of Quantum
MEG: Magnetoencephalography
NQI: National Quantum Initiative
SDGs: Sustainable Development Goals
SeGQuRo: Strengthening and Entangling Global Quantum Roots
STI: Science, Technology, and Innovation
OPM: Optically Pumped Magnetometers
PQC: Post-quantum Cryptography
QDNL: Quantum Delta Netherlands
QEI: Quantum Energy Initiative
QKD: Quantum Key Distribution
QT: Quantum Technologies
QTRL: Quantum Technology Readiness Level
QuTE4E: Quantum Technologies Education for Everyone

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Paper 1.1: “The landscape of the quantum start-up ecosystem” (Seskir, et al., 2022a)

Paper 1.2: “Global innovation and competition in quantum technology, viewed through the lens of patents and artificial intelligence” (Seskir & Willoughby, 2023)

Book Chapter 1.3: “Subchapter 7.2.2: Milestones of research activity in quantum computing” (Seskir & Biamonte, 2024) in “Chapter 7: Physics for secure and efficient societies” in *EPS Grand Challenges – Physics for Society in the Horizon 2050* (Barbato, et al., 2024)

Paper 1.4: “Building a quantum-ready ecosystem” (Purohit, et al., 2024)

Paper 1.5: “Quantum games and interactive tools for quantum technologies outreach and education” (Seskir, et al., 2022b)

Paper 1.6: “A Chronicle of Quantum Technologies in Game and Software Development” (Skult, et al., 2024)

Paper 1.7: “Educating to the “Culture” of Quantum Technologies: A Survey Study on Concepts for Public Awareness” (Seskir, et al., 2024b)

Paper 1.8: “Why teach quantum in your own time: the values of grassroots organizations involved in quantum technologies education and outreach” (Genenz, et al., 2025)

Conference Proceeding 1.9: “Games for Quantum Physics Education” (Chiofalo, et al., 2024)

Book Chapter 1.10: “Communicating Quantum Technologies in an Era of Mistrust and Misinformation” (Goorney, et al., 2024a)

Conference Proceeding 1.11: “Exploring Pitfalls for Defence and Security by Narratives on Quantum Technologies” (Seskir, et al., 2024a)

Paper 2.1: “Democratization of quantum technologies” (Seskir, et al., 2023a)

Paper 2.2: “Communities of quantum technologies: Stakeholder identification, legitimation and interaction” (Umbrello, et al., 2024)

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Prologue

I am writing this prologue from a cafe in Geneva (well, a Starbucks) on 12th October 2024 after attending the fifth anniversary of the Geneva Science and Diplomacy Anticipator (GESDA) Summit. There were UN officials (including the Director-General of the UNOG), state ambassadors, parliament and cabinet members from all around the globe, academic researchers from prestigious universities and NGO representatives, and one of the keynote topics was the Open Quantum Initiative (OQI) of GESDA focusing on democratizing quantum computing, which is now operated under CERN, possibly the largest internationally oriented scientific organization in the world. There was a strong consensus at the meeting that it is time to reach to the underserved geographies and utilize quantum technologies towards the goal of supporting progress on achieving the UN SDGs. All this, just 10 years ago, would have been unimaginable to most researchers in the field, yet, quantum technologies wasn't entirely a niche topic back then. In the US, Time Magazine had a quantum (annealing) processing unit from D-Wave on its cover on February 17th 2014 with the text "*It promises to solve some of humanity's most complex problems. It's backed by Jeff Bezos, NASA and the CIA. Each one costs $10,000,000 and operates at 459° [Fahrenheit] below zero. And nobody knows how it actually works. - The Infinity Machine by Lev Grossman*," all in caps (Grossman, 2014). In Europe, Tommaso Calarco, dubbed Mister Quantum Manifesto by Helmholtz, was already trying to arrange a meeting with the Commissioner for the Digital Economy and Society for trying to convince him to a billion-euro flagship program in addition to the two existing EU flagship projects on the brain and graphene (Kirchgeßner, 2020). In China, the QUantum Experiment Science Satellite (QUESS) prototype satellite, which eventually became the world's first publicly known "quantum satellite" launched in 2016, was being built while it's Critical Design Review (CDR) was filed and the ground station in Xinglong was being completed (Pan, 2018), led by Jian-Wei Pan, China's "father of quantum" as dubbed by the MIT Technology Review (Giles, 2018). There were already more than 60 quantum start-ups founded around the globe (Seskir, et al., 2022a), more than 6000 patents granted (Seskir & Willoughby, 2023), and 30.000 academic publications on quantum technologies published (Seskir & Aydinoglu, 2021). Yet, the situation today was unimaginable back then for most researchers in the field, and not everyone is convinced today either.

The quantum technologies community consists of a variety of positions when it comes to the timeline question. Some believe it is just hype and even a bubble, quantum technologies (especially computing) won't be societally relevant for at least the next 20 years and some even joke as it is the new fusion and will continue to be "only 20 years away" for the foreseeable future. This is a funny camp, where it is equally likely to find quantum skeptics and active researchers involved in quantum research taking this position. Others believe there has been considerable progress since early 2000s and especially for the last 10 years almost all the big-tech companies abode by their public roadmaps, hence it is only expected that they will continue delivering in accordance with their roadmaps, where most companies promise industrially relevant devices by mid-2030s. This camp consists mostly of people who have already invested in the technology, either career-wise, financially, or emotionally. And finally,

some are quite enthusiastic, and believe there will be rapid progress and useful quantum computers in just a few years. This camp usually consists of those who are looking for investment in delivering those magical devices or some kind of advantage using those devices, or outsiders who are not directly involved in quantum technologies but are exposed to the narratives promoted by the overly enthusiastic community members.

In the midst of all these, I was a PhD candidate in Physics in Turkey with a focus on quantum networks. I had a peculiar background, as I had both my B.Sc. and M.Sc. thesis on quantum information theory, working on a relatively distant future quantum technology (the quantum internet), yet I also had a M.Sc. degree from the Science and Technology Policy Studies (STPS) department with a thesis on the current state of quantum technologies published in 2019 (Seskir, 2019). As the pandemic hit in 2020, during those long days at home, I finally decided to drop my PhD in Physics and focus on the potential impact of quantum technologies on society in the future. Yet, one question was particularly interesting for me at that time, the impact of which future quantum technologies? There were (and still are) many proposals to physically realize quantum computers, using different hardware modalities such as superconducting devices, ion traps, photonics, diamonds, and other more exotic ideas such as topological systems. For the quantum internet, almost all seemed up in the air, there were proposals using classical repeaters, proposals using quantum repeaters but needing quantum memories which at the time basically didn't exist, and combinations of these. Also, these were just the technical aspects, I realized even back then that there were other layers involved in forming the future of these technologies, the ethical, legal, and social aspects (ELSA), and they were as critical as the technical layer. For example, all the proposals of quantum key distribution (QKD) networks, a technology promising to provide unconditional security against eavesdroppers and ultimate privacy to its users, were implicitly assuming that this would actually be legally and politically allowed. In fact, both the Snowden revelations (MacAskill, 2013) and the well-known Apple–FBI encryption dispute (Benner & Lichtblau, 2016) in the US, and the so to speak Chatkontrolle (Breyer, 2024) debates in the EU were indications that such a public infrastructure of QKD networks providing ultimate privacy and unconditional security to civilian end-users might have more challenges against them than just the technical difficulties of inventing quantum memories with enough storage time and high fidelity to make it technically possible. As it was stated by one of my favorite quotes: "*…the space of the technologically possible is much greater than that of the economically profitable and socially acceptable*" (Perez, 2010), and just because something is technologically possible doesn't mean that it will become an economic or social reality. With these in mind, I formulated my research questions back then:

- How are quantum technologies imagined, envisioned and aimed to be realized in our current techno-societies?
- What are the possible path dependencies for future scenarios for the development of these technologies?

As it is often the case in the STS tradition, I abide by the advice of providing one's own history and situation as a useful practice for positioning any study at hand. IBM launched their first publicly available quantum processor unit in May 2016 (Vu, 2016). It was a five qubit device and

computationally less powerful than any average calculator available, yet it was novel, publicly available, and free to use. I started playing with it via its drag and drop interface. It was basically a toy, but as a first year PhD student on the topic, it was a great joy to play with it and explore. In 2017, IBM introduced their quantum programming library Qiskit (IBM, 2024) built on a popular and easy to learn programming language Python, which allowed more serious research opportunities with their devices. I didn't know Python back then, but I started learning it and using Qiskit. There weren't almost any educational materials on how to learn quantum programming, but there was a growing community and IBM was providing some support in promoting and expanding their new library. Meanwhile, I was employed full-time by my university at the Department of Physics primarily for supporting teaching activities.

By early 2018, I was pretty certain that the IBM devices and Qiskit as a programming language (now containing multiple libraries for different purposes) were here to stay. Yet, it was still pretty new and only a handful of people were really aware, and even less in countries like Turkey. I decided to act on it, reaching out to professors in different departments, who connected me to others. In the end, I reached out to a group led by an early career researcher with the support of an established professor at the University of Latvia's Faculty of Computing with almost the same idea, spreading awareness and expertise on this novel programming language, first to Eastern Europe, and later to the world. This led to us organizing the first quantum programming workshop in Turkey in 2019 as part of the QDrive project (Yakaryilmaz, 2019). By the end of 2019, we had the organization now called QWorld with its first QCousins, local groups of researchers and enthusiasts of quantum technologies gathered together for the purpose of increasing awareness, providing education and outreach, primarily for free through volunteering efforts. As of today, QWorld is active in more than 30 countries, most of which are in underserved geographies (usually called the Global South). In the last five years, I have committed probably more than 1000 active volunteering hours to QWorld and QTurkey, which undoubtedly impacted my position and perception of the topic while carrying out my studies related to this thesis work.

As stated above, the first proposal of this thesis was drafted in 2020. A lot has changed since 2020. There were three developments that led me to amend my research questions and alter my research methodology since then. First, was the many discussions that came out of the way the COVID-19 pandemic was handled and the public perception of it. As it is stated by Timothy Caulfield, research director of the Health Law Institute at the University of Alberta at the time, in terms of how science informs and impacts decision making "*the public saw how the sausage was made, and they didn't like what they saw*" (Cross, 2021). From the debates on vaccines to lockdowns, from the pandemic era policies leading to one of the largest wealth transfer of recent times (Allen & Rebillard, 2021) to how some public officials brazenly utilized scare tactics on an already scared public (Catt, 2023), those two to three years blew a whole in public trust in the science system and infrastructure we have. Yet, they also showed how remote work and online collaboration can support global efforts even beyond previous expectations. QWorld was a good example of this for me, but it wasn't the only example. Starting in late 2020, with the realization that the pandemic era lifestyle is going to be around for at least a while, I got involved in the ongoing efforts of developing pilot projects (which were not going to be funded but run via

voluntary contributions) with a community of researchers clustered around the QTEdu Coordination and Support Action (CSA) of the Quantum Flagship. That led to the formation of the Quantum Technologies Education for Everyone (QuTE4E) project in late 2021, in which I took the role of co-coordinator together with Marilu Chiofalo from University of Pisa. The project we proposed and later ran had an explicit Responsible Research and Innovation (RRI) dimension in terms of deliverables, not because we had to (remember that none of the projects were funded) but the core community of that project believed it was important for the education and outreach activities related to quantum technologies to have a RRI dimension. This allowed me to embed myself in a diverse community of education researchers and practitioners focusing on quantum technologies, who also cared deeply about the RRI topics. Taking an active role in the coordination of that project and the community helped me formulate and work on several key issues related to this thesis, which led to four out of the 14 publications of this thesis work.

The second was the Russian invasion of Ukraine that started on 24th Feb. 2022. This impacted my thinking and approach to this thesis on three fronts. First was very personal. In 2019 I was invited to Moscow for an interview for a position at The Skolkovo Institute of Science and Technology related to running an innovation landscaping study for quantum computing applications. After my initial visit I decided it might be a suitable position for me after my PhD. My wife, in all her wisdom, took a principled stance stating that she won't be moving from Erdogan's Turkey to Putin's Russia, and if I were to go, I would go alone. I decided not to take the job but continue my collaboration online with the professors who invited me to the project in the first place, which again proved to be a good decision as the COVID lockdowns hit in March 2020 making any travel quite challenging anyways. It was a great learning experience and the professors were in favor of open science and collaboration, one even co-authored a comment piece titled "Keep quantum computing global and open" in Nature (Biamonte, et al., 2019). Neither of them were Russian, and neither lives in Russia today. One moved to HHL Leipzig, Germany as a full professor, the other moved to kickstart a new institute in Quebec, Canada. This was a personal lesson on, i) to always listen to the wisdom of my wife, and ii) regardless of how influential the individual actors are in their relevant ecosystems, politics in the end has a tendency to trump all goodwill.

The second front the invasion of Ukraine impacted this study was a direct first-hand observation on how ethical dilemmas and debates can emerge, not merely via philosophical contemplation, but very practically as a response to real-time events. After the Russian invasion started and the European sanctions were being discussed on Russia, especially on the topic of freezing scientific collaboration, a rift emerged in QWorld. As it was an organization primarily sprung out of Eastern Europe, our colleagues in the countries directly impacted by the Russian invasion wanted to kick-out QRussia (which was established in December 2019), even if only as a symbolic action (all the educational materials provided by QWorld is open source and publicly available, hence no actual resources were provided to QRussia other than the ones they were able to reach themselves freely at that point). It was a fierce debate, there were ethical, legal, and social arguments provided from both sides. QRussia (although named as Russia) was a group of researchers and enthusiasts primarily out of the Kazan region, which is a part of the Russian Federation but officially is the Republic of Tatarstan. On what grounds would QWorld

kick them out, what kind of a signal would it send to all the other members from the Global South? But again, on what moral or legal grounds could QWorld keep QRussia under its umbrella given the circumstances? There were those on either side claiming it is ‘unethical’ and against the values of QWorld to do what the other side asks of. It was also quite interesting to see the level of personal care involved, for example when the point of should we ask QRussia to make a statement against the actions of Moscow, it was the side who stood in favor of kicking out QRussia that argued against it first on the grounds that it might endanger our colleagues in Kazan. It was clear that they wanted an action against QRussia, but not against our colleagues who are part of QRussia. After several weeks of fierce discussions, some compromises were made from both sides, but QRussia was still kept listed under the QWorld umbrella. This was a very instructive experience for me on how explicit values of organizations (such as inclusivity and openness) can be understood by different parties in an organization on the same topic from different contexts may lead to opposing decisions as the ‘right one’. Values might frame the debates and discussions, but in practice values alone can’t allow organizations to make the ‘right’ decisions.

The third front was about how the invasion of Ukraine led to further securitization of quantum technologies. Quantum technologies were always highly relevant for security and military applications. The first real widely known technological promise of quantum technologies was the QKD protocol proposed in 1983 (published in 1984) by Charles Bennett and Gilles Brassard called BB84 (Bennett & Brassard, 1984). The second real promise was Peter Shor’s algorithm he published in 1994 (Shor, 1994), showing exponential speed-up for finding the prime factor components of any number, a cryptographically highly relevant mathematical problem that one day might have led (and still may lead) to the collapse of public key cryptography infrastructure that enables encrypted communications via the internet. The Snowden Revelations revealed that the NSA had a $80 million project titled “Penetrating Hard Targets” on developing a cryptographically relevant quantum computer (Rich & Gellman, 2014), and actually NSA had been collaborating with universities publicly on developing quantum computers as early as 2006 (IOPP, 2014). The third promise, using quantum sensors for identifying stealth objects, such as quantum radars (Durak, et al., 2022), or using quantum gravimeters to identify submarines (Qiu, et al., 2016) have been around for years. Yet, it was primarily the Russian invasion of Ukraine that accelerated the process of security stakeholders getting further involved into the development and spread of quantum technologies. NATO published its quantum strategy in early 2024 (NATO, 2024), and many countries including Germany, the US, the UK, and France (Sparkes, 2024) started implementing strict export controls due to dual-use concerns of even early quantum technologies. This shifted the findings of my thesis quite a bit from its earlier formulation, as previously the stakeholders who were pushing for global cooperation and open science were more vocal, while in the last couple of years increasingly the security stakeholders are getting more and more involved in the overall ecosystem of quantum technologies and expanding the scope of what is deemed ‘relevant’ for security purposes. To keep track of what is going on and to contribute to the discussions we submitted a paper proposal to the NATO IST-SET-198 Research Symposium on "Quantum Technology for Defence and Security” organized in Amsterdam (Oct. 2023) with two colleagues and to our surprise we were accepted and even actively welcomed, which led to a publication titled Exploring Pitfalls for Defence and

Security by Narratives on Quantum Technologies (Seskir, et al., 2024a). This followed by an invitation to an event titled Responsible Innovation in Defence and Security co-organized by BENELUX and NATO (FPS, 2023) later in 2023, which later led to me joining a NATO Science & Technology Organization (STO) Working Group on Quantum Technology Vulnerabilities. Simultaneously, to have at least some understanding of what non-NATO organizations are doing, I attended and presented at a conference titled European Conference Quantum Technologies for Defence Current and Future Capabilities organized by the European Network of Defence-Related Regions (ENDR) in March 2024, which led to being a member of the newly formed Quantum Security and Defence Working Group, which can be classified as a stakeholder group consisting of many individuals from different organizations focusing on defence and security relevant topics in quantum technologies. My brief time with these organizations and those several events were particularly informative. For example, as an outsider of the defense ecosystems, I had no idea about the points of contestation between organizations such as NATO and the European Defence Agency (EDA), which in hindsight makes a lot of sense given both are security policy providers to the same region, which necessarily leads to both collaboration and competition at times (similar to OECD and UNESCO or World Bank and IMF).

The third development that had a significant impact on both this thesis and the quantum technologies ecosystem was the public release of ChatGPT by OpenAI on 30th Nov. 2022. I ran a bibliometric and patent analysis comparing publications and patents in artificial intelligence (A.I.) and quantum technologies in April 2022, which resulted in a 24 page internal report, and in my infinite wisdom, I didn't choose to publish it. A.I. was already performing so greatly in all the metrics, I assumed it should have been widely known that A.I. was taking off exponentially and there was no point in trying to publish something so obvious. For some context, you can check Figures 1 and 2 for academic publications and Figures 3 and 4 for patents granted on the topic.

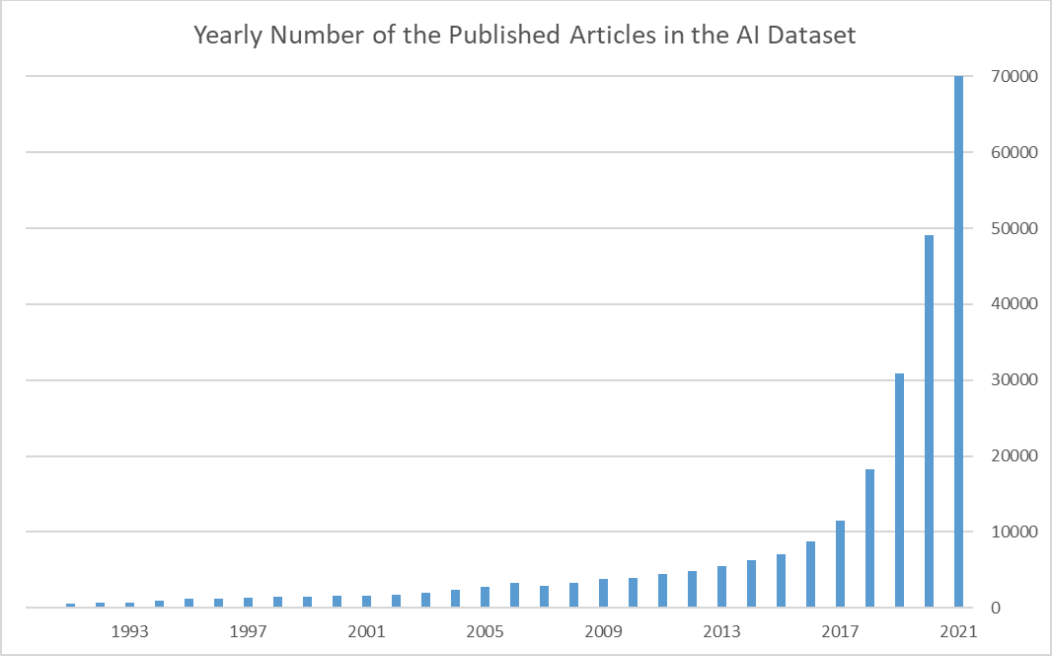


Figure 1: The yearly number of published new articles in the A.I. publications dataset

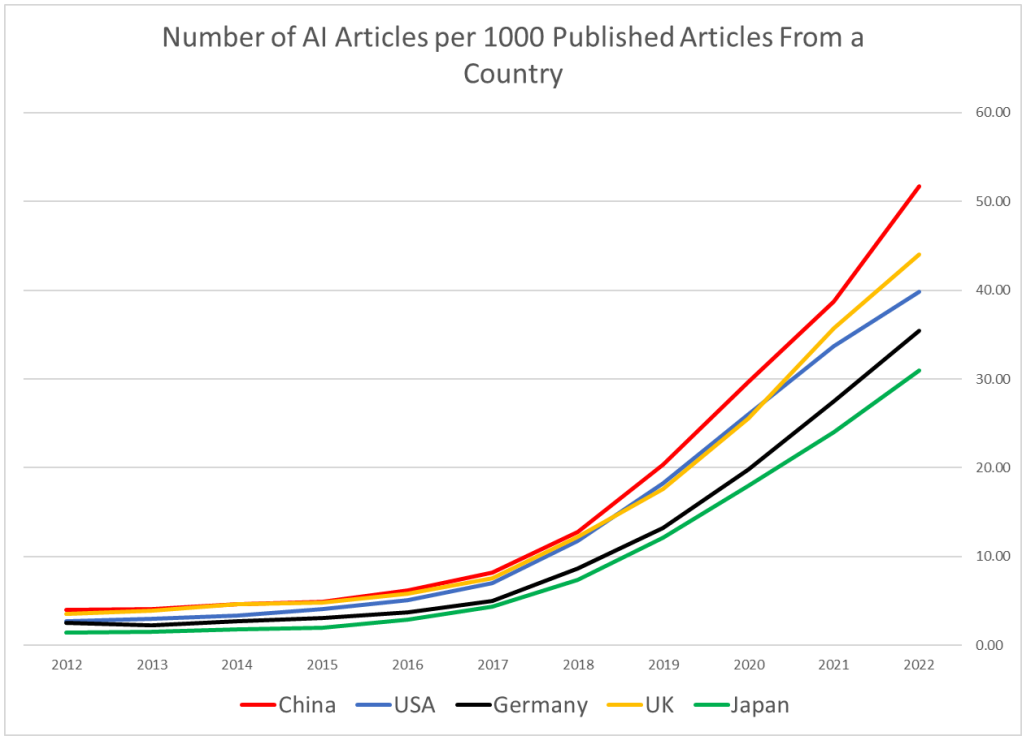


Figure 2: Number of A.I. articles published per 1000 total articles coming out of those countries

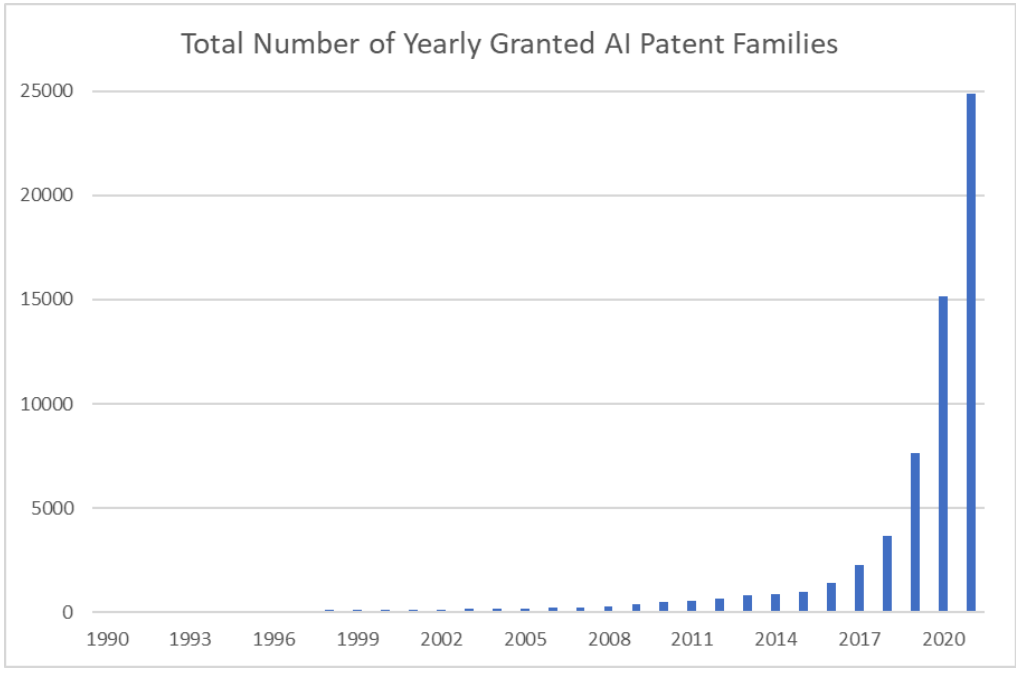


Figure 3: The yearly number of granted patents families in the A.I. patents dataset

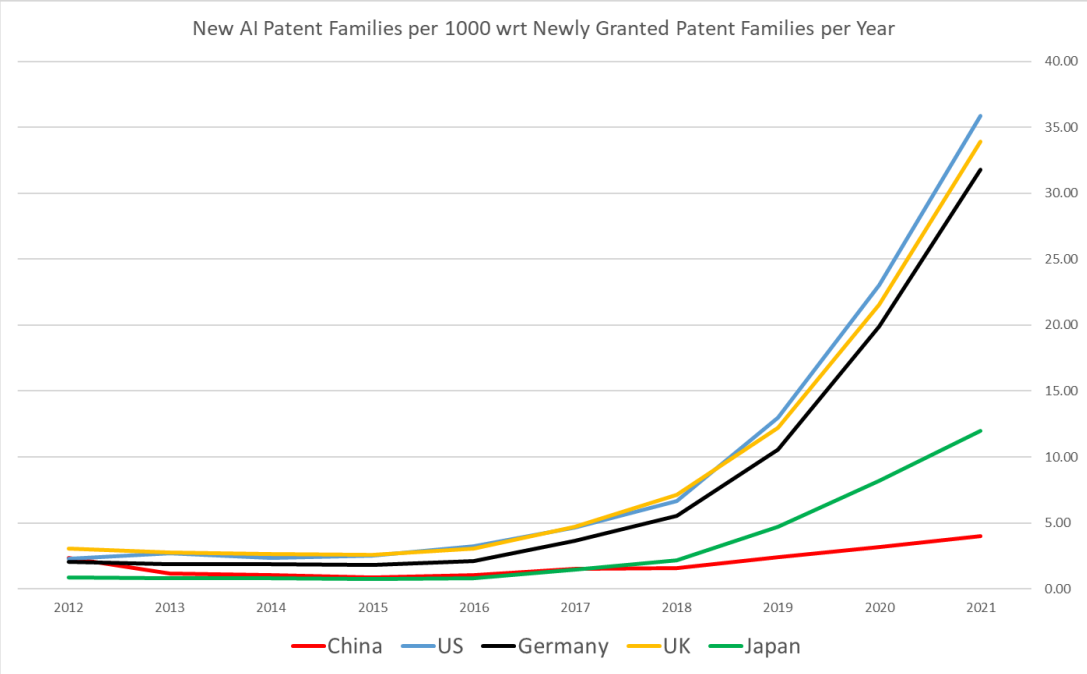


Figure 4: Number of A.I. related patent families per 1000 total patent families coming out of those countries

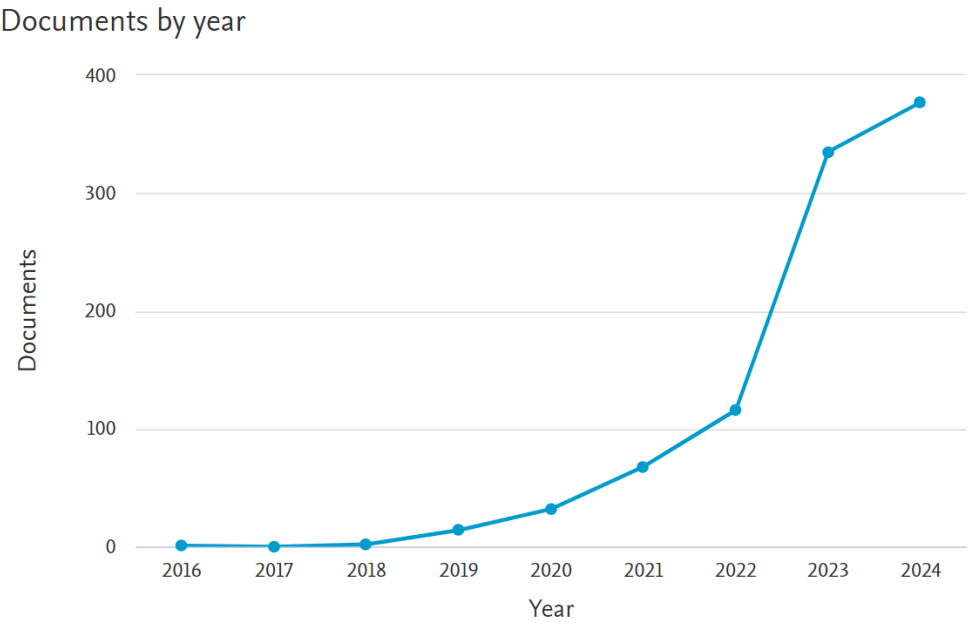


Figure 5: Number of articles published per year as of Sept. 2024 with keyword “responsible AI”

Anyone looking at these numbers and graphs would have guessed that something big is happening in the field of A.I., yet no one, except a few dedicated researchers who have been following the field for a long time (Binaire, 2016), foresaw the potential impact of and panic caused by introduction of a clever chatbot (i.e. ChatGPT) to the wider public. This, I would say,

caused a heightened vigilance in the governance bodies against other emerging technology topics. At most of the debates and discussions on why or how to regulate quantum technologies, references to A.I. and ChatGPT became almost compulsory. This heightened vigilance can be seen in the data as well. A Scopus search on the keywords “responsible AI” and “AI ethic*” reveals the ChatGPT bump very clearly from 2022 to 2023, which can be seen on Figures 5 and 6.

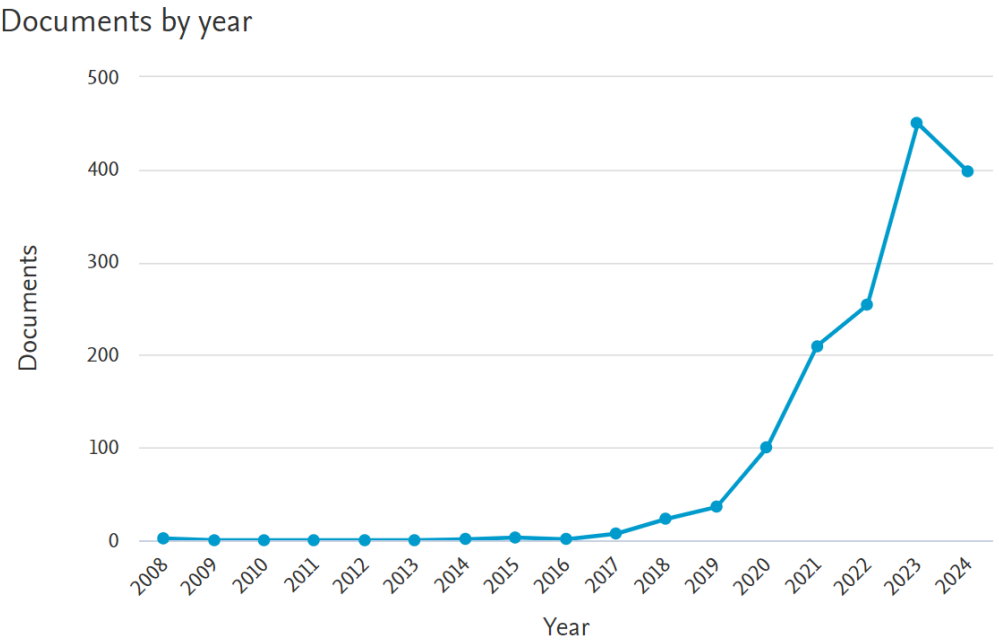


Figure 6: Number of articles published per year as of Sept. 2024 with keyword “AI ethic*”

An updated search (on 12th Oct. 2024) shows that the query "responsible AI" OR "AI ethic*" returns 2414 academic publications on Scopus out of which 1573 of them were published in 2023 and 2024, which corresponds to 65% of the total literature. In contrast, the query "responsible quantum" OR "quantum ethic*" on Scopus returns only 12 publications in total, 8 of which were published in 2023 and 2024, again 66%. This is consistent with the literature, a study titled “Auditing the ‘Social’ of Quantum Technologies: A Scoping Review” was run by Wolbring in 2021 on the entirety of quantum physics and technologies literature (Wolbring, 2022) and identified the lack of use of any keywords on social aspects. ELSA of quantum technologies, until recently, were almost entirely missing from the academic publication landscape.

These three developments, combined with my background and what I learned from the PhD modules at ITAS nudged me away from focusing solely on the development of quantum technologies towards considering more on how to do it responsibly, and what are the conditions of that. This, of course, also requires a solid understanding of where the field currently is, hence it is built on my previous and ongoing studies during the earlier days of my PhD. And, thanks to the support provided by ITAS I also helped kickstart an event series called Responsible Quantum Technologies (ResQT) in December 2021, just a couple of months after I arrived in

Karlsruhe. In April 2024, we organized the fourth iteration of ResQT with almost 40 speakers and panelists spread over three days, covering topics ranging from education to art, from geopolitics to climate change. This was also a resource I didn't expect to have at the beginning of my PhD but deeply appreciate and the one which helped me to make the topic-wise transition from investigating the conditional futures of quantum technologies to conditional futures of responsible quantum technologies.

PART I

Introduction

The world is going through a transformation; technologically, politically, and societally. A new set of emerging technologies are rapidly being developed and introduced to markets without much deliberation or contemplation on their impacts on societies and the established order. This coincides with a set of policy decisions and actions taken by certain geopolitical actors (such as the US, the EU, and China), which some name as a new era of de-globalization (Keller & Marold, 2023). Meanwhile, our societies are in a state of being highly polarized, fueled by uncertainties about the future and how to deal with the crises of our times. This highlights the relevance of Technology Assessment (TA), whose primary goal is to anticipate both intended and unintended consequences of technological transformations on society.

This is not the first time that the world is going through such a transformation, as the history of modern civilization is a continuous series of transformation and transition periods. Technology always had a major role in how these periods evolved. Quantum mechanics had its fair share to play since the early stages of the 20th century. From the development of nuclear weapons to smartphones, its impact was considerable on both geopolitical, economic, and societal fronts. Invention of the transistor due to the discovery of semiconductors enabled a wide range of societally impactful artefacts which led to personal computers and the internet. Containing the atom resulted in the spread of nuclear power stations and all the public debate and controversies that followed. There were other inventions as well such as MRI devices that are commonly used in the medical field, lasers that have a wide range of applications from fiber optic communications to color printing in our own apartments, and particle accelerators which are used to explore the limits of our knowledge of elementary particles and in food preservation by irradiation. All these inventions and discoveries are associated with knowledge emanating from the formulation of standard quantum mechanics that goes back to the 1920s and is dubbed by some as the outcomes of the first quantum revolution.

Since the 1980s, a new period in the history of quantum mechanics has begun, which is leading to the invention and development of novel tools, that some call as the second quantum revolution (Dowling & Milburn, 2003). Combining the fields of information science and quantum mechanics in the 1980s led to the formation of a new field called quantum information science. In 1984 (Bennett & Brassard) and 1991 (Ekert) there were two important demonstrations of how this new formulation can yield novel technological artefacts that can provide unconditional cryptographic security in communications. In 1994, a researcher named Peter Shor developed an algorithm, now called Shor’s algorithm, which showed that with a quantum computer one can factor a number into its prime factors exponentially faster than a classical computer. These two combined resulted in major interest in the field from defence research agencies like DARPA and security agencies like the NSA in the US, as the difficulty of prime factorization was the main mathematical tool that public-key cryptography was built upon. Anyone with a quantum computer could read any online communication. The early 2000s saw a rise in promises, where

even the first commercial quantum computing company was founded in Canada in 1999. Yet it proved to be a gargantuan task to actually build these devices, and the limited public interest slowly faded away by early 2010. This was, until IBM put a 5-qubit quantum computer prototype on their cloud for free in 2016, for anyone and everyone to access the device online and try testing out what a (toy level) quantum computer can (and can't) do. Simultaneously, China launched the world's first quantum communication satellite called Micius (Mozi) in 2016, in collaboration with the Austrian Academy of Sciences led by Anton Zeilinger, who received the Nobel Prize in Physics in 2022. These coincided with the publication of the Quantum Manifesto in May 2016 (De Touzalin, et al., 2016), signed by more than 2000 researchers in Europe, calling the European Commission to launch a €1B Flagship initiative on quantum technologies in 2018 within the European H2020 research and innovation framework programme.

As of late 2024, there are more than 25 countries with national quantum initiatives, committing a total of €40B public funds by 2030, more than 500 start-up companies were founded since 2016 solely focusing on the areas of quantum computing, quantum communications, and quantum sensing, and major military alliances (such as NATO) have developed quantum specific strategies. The publicly available IBM quantum computers in their cloud systems and their open-source quantum programming language (Qiskit) have over 600.000 users worldwide, and other cloud providers such as Microsoft Azure and Amazon's AWS provide commercial access quantum computers to paying customers from a wide range of hardware providers. The first European Quantum Data Center housing two utility-scale quantum computers (located in Ehningen, Germany) was formally launched at an event attended by German Chancellor Olaf Scholz in October 2024. In less than 10 years, QT emerged as a field of strategic importance, so much so that in 2024 the US, the UK, the Netherlands, Germany, Spain, and others introduced strict export control regulations on the export of these devices to other countries.

The rapid emergence of quantum technologies underscores a particular challenge for TA, as assessing new and emerging sciences requires engaging with critical uncertainties and speculative futures. Given all these, the questions on societal relevance and risks posed by the way these technologies are being developed and introduced to markets are also expected to start gaining momentum, yet this is not the case compared to other emerging technologies (such as A.I.). As of October 2024, there are more than 2000 Scopus indexed publications with the keywords "responsible AI" or "AI ethic*"[1], in contrast, there are only around 10 with keywords "responsible quantum" or "quantum ethic*", and in total less than 100 on the potential societal impacts of quantum technologies (excluding the education and workforce development aspects). There is only one country (the Netherlands) with a dedicated funding line for ELSA research on QT (a total of €20M). One of the most common replies one gets as the reason for the relative lack of activities in these topics is that we are too early for quantum technologies to discuss these questions, and that their societal relevance is still something in the future. In the technology assessment literature, this situation was explored more than 40 years ago by David Collingridge (1980) and formalized in a way today referred to as the Collingridge dilemma. Simply put, as a technology progresses the evidence of its impact increases while the possibility of social control over its design trajectories decreases (see Figure 7).

[1] ethic*, the asterisk here allows search of any keyword that starts with ethic, such as ethics, ethical, etc.

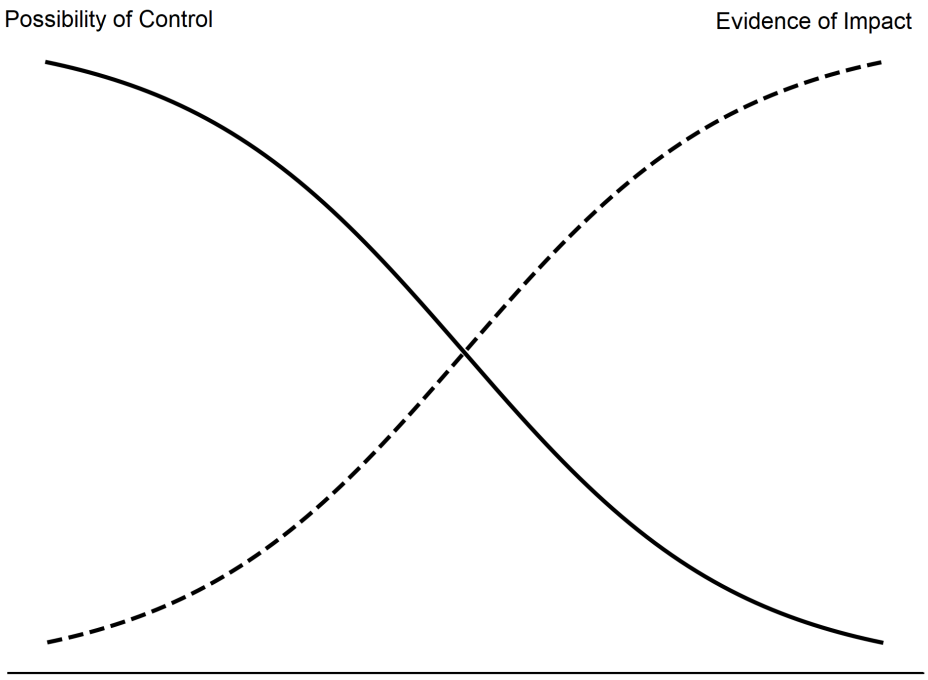


Figure 7: A basic formulation of the Collingridge dilemma (1980)

The Collingridge dilemma, combined with the conceptual evolution of path dependence literature, provides the two legs this thesis stands on. Path dependence is a concept utilized to investigate the trajectories of technologies (Dosi, 1982) and to study the historical events (Arthur, 1989) that led to the development of current technologies. Looking at such histories shows that the development is not solely accomplished by technical feats. This has been an important topic in discussions on the development of competing technologies since the early 1990s (Arthur, 1989, 1990). Such arguments first developed mainly out of evolutionary economics literature in the 1980s (David, 1985). This line of thinking laid the path for connecting different spheres of the socio-technical realm, allowing further elaboration on the development and adoption of technology not just in accordance with its technical feats. Later to be formulated in a format where studies in these topics can guide policymaking and funding decisions (Cowan, 1991), and how certain historical conditions may lead to societal lock-in to technologies that are deemed as inferior in one context or another (Liebowitz & Margolis, 1995). A common example in the literature of this is the format war between Betamax and VHS (Arthur, 1989), where the author studied a technically inferior technology becoming the standard through social forces (VHS over Betamax).

Later developments in the literature further expanded these approaches, and one of the main paths of this expansion was the development of the social shaping of technology (SST) approach (MacKenzie & Wajcman, 1999). This approach has also been utilized in the context of technology foresight (Jørgensen, Jørgensen & Clausen, 2009). Although SST is more closely related to the tradition of the social construction of technology (SCOT) approach (Pinch & Bijker,

1984), it is possible to stretch this idea to better fit into a more suitable setting for foresight purposes, such as including techno-economic networks (Callon, 1990) and theories on how technological leadership changes, such as the techno-economic paradigm approach (Perez, 2010). And finally, to the concepts of vision assessment developed by the TA and STS communities (Lösch, et. al, 2019).

Collingridge dilemma informs us that possibility of social control over a technology diminishes as the technology matures and the path dependence literature informs us that early decisions on the development trajectory of a technology results as lock-in to certain paths which are later either extremely difficult or sometimes almost impossible to phase out of. Therefore, having an anticipatory approach, trying to identify the most desirable paths (so that the development trajectory can be guided towards them) or identifying the least desirable paths (so that the development trajectory can be guided away from them), and capacity building on how to guide the development trajectory of these technologies becomes a relevant activity for any ecosystem around an emerging technology. This thesis aims to contribute to these efforts by studying the quantum technologies ecosystem through the lenses of two questions:

- **RQ1:** How can responsible quantum technologies be imagined, envisioned and realized by the quantum technologies community?
- **RQ2:** What are the relevant topics and possible critical path dependencies for the development of these technologies responsibly?

In this work, the terms responsible and responsibility refer to an anticipatory, inclusive, reflexive, and responsive approach to technology development, as outlined in the Responsible Research and Innovation (RRI) literature (Stilgoe et al., 2013). Responsibility here serves as a normative framework, emphasizing not only ethical considerations at the individual or organizational level but also collective societal accountability in shaping desirable technological futures (von Schomberg, 2013).

Yet, to be able to address these research questions, first one needs to explore how TA (and STS) has been applied in other technology domains. For that, the next section is dedicated to the TA (and STS) discussions on three other technologies that are usually used within the community to draw analogies from; A.I., nanotech, and nuclear.

Overview of TA for A.I., Nanotechnology, and Nuclear Technology

TA and STS emerged in the late 20th century as interdisciplinary approaches to understand and govern the societal impacts of new technologies. The U.S. Congress established the Office of Technology Assessment (OTA) in 1972 to equip policymakers with "*competent, unbiased information*" on the potential "*beneficial and adverse*" impacts of technological applications. Since then, a global network of TA institutions has evolved, spreading to Europe and beyond (Hennen, et al., 2023). STS scholarship, for its part, has critically examined how science, technology, and society co-evolve, emphasizing that technological development is not isolated from social values and political choices (Jasanoff, 2022). This section briefly covers the main

scientific outcomes of TA and STS debates in three domains; artificial intelligence, nanotechnology, and nuclear technology. These three are usually the ones that are mentioned the most in the community when responsible QT efforts are being discussed, either as good examples, such as what we can learn from the successes (like those in the nano field) or as cautionary tales (like the growing debates in the A.I. field). An overview of how scholarly and policy debates have shaped understanding, governance, and development of these technologies are provided below.

TA of Artificial Intelligence

Artificial intelligence has periodically surged in capability and public attention since the 1970s, prompting both optimism and caution, making it an active area of interest for TA and STS researchers. In the 1980s, the OTA and other analysts assessed the first wave of A.I. applications (e.g. expert systems), identifying their promise for productivity alongside fundamental technical limitations (OTA, 1985a) . Expert systems were the "*first real commercial products*" of decades of A.I. research but studies also warned of "serious weaknesses" requiring "fundamental breakthroughs" for them to be adopted widespread. Early computer scientists and STS-oriented thinkers raised ethical concerns about the impact of A.I. on employment, privacy, and human dignity as far back as the 1970s (Weizenbaum, 1976). These initial debates established a pattern of assessing societal implications of A.I. in parallel with its technical progress.

As A.I. technology advanced (especially with data-driven machine learning in the 2000s and 2010s), TA and STS discussions broadened to issues of algorithmic bias, transparency, accountability, and safety. Critical scholars examined how A.I. systems can unintentionally embed social biases and challenged the field's implicit assumptions of objectivity (Weber & Prietl, 2021). This scholarly scrutiny, often informed by feminist and critical data studies, laid groundwork for the wave of A.I. ethics initiatives in the late 2010s . Meanwhile, policy-oriented assessments highlighted both benefits and risks of A.I. For example, the Government Accountability Office (GAO) in the US, which took over the technology assessment responsibilities of OTA after OTA was shut down, continued reporting on both the benefits of A.I. such as improving human life and economic competitiveness, while highlighting the novel risks posed by widespread introduction of A.I. in areas like security and employment (GAO, 2018). By the 2010s, consensus emerged that proactive governance was needed even as A.I. research continued.

It can be argued that the scientific outcomes of these debates resulted in new frameworks such Trustworthy A.I. and A.I. governance. A proliferation of A.I. ethics guidelines appeared worldwide, by 2023, there were hundreds of guidelines and recommendations on A.I. governance (Corrêa, et al., 2023). Beyond the academic literature, there were notable cases such as the European Commission High-Level Expert Group on Artificial Intelligence (2019) which defined seven key requirements for "Trustworthy A.I.," human agency, technical robustness, privacy, transparency, diversity/nondiscrimination, societal well-being, and accountability, and the OECD principles on artificial intelligence (2019), which aimed at promoting "*innovative, trustworthy AI that respects human rights and democratic values*."

These resulted in the formulation of what is commonly referred to as the AI Act by the European Union (2024), a comprehensive regulation that establishes legally binding rules for the development, marketing, and use of A.I. systems within the European Union, based on a risk-based classification. It prohibits certain A.I. practices, imposes strict requirements on high-risk A.I. systems (such as, transparency, human oversight, conformity assessments), and mandates accountability from both providers and users to ensure safety, fundamental rights, and trust in A.I. technologies.

One might assume that having established principles and governance structures is the pinnacle of TA/STS achievements regarding an emerging technology, yet as Figure 6 shows, debates and discussions on responsible A.I. and A.I. ethics are actually accelerating instead of reaching a saturation point. Introduction of novel A.I. products (like ChatGPT and following models), and especially the diversification of the A.I. players' landscape, such as the development of Chinese DeepSeek (Ng, et al., 2025), are sure to bring points of contestation and new debates that go beyond the more commonly discussed issues of bias, safety, and innovation. This can be seen even in our local environment, where at ITAS, four out of approximately 30 ongoing (or recently completed) PhD dissertations are on various A.I. topics (Ackerl, 2025; Bareis, 2025; Martin, 2025; Vetter, 2025), indicating that instead of saturation, the interest in A.I. is growing.

TA of Nanotechnology

Nanotechnology, the manipulation of matter at the nanoscale, rose to prominence in the 1990s and 2000s amid both great promise and uncertainty. Early visionary forecasts (such as molecular assemblers and "nanobots") fueled optimism about revolutionary applications in medicine, energy, and materials. However, TA and STS scholars quickly pointed out a dual reality: alongside potential benefits, nanotech could pose new health, environmental, and ethical challenges (the specter of unpredictable risks such as nanoparticle toxicity or even far-fetched scenarios like "grey goo"). In the mid-2000s, a seminal Royal Society (2004) report urged proactive risk research and public engagement for nanotechnologies, embodying the TA principle of early warning. Around the same time, the U.S. National Nanotechnology Initiative (NNI) began allocating funds to study Environmental, Health, and Safety (EHS) impacts of nanomaterials (NRC, 2006), and the UK and others held public forums on nanotech, all reflecting an anticipatory approach influenced by TA/STS perspectives.

The most significant outcome of nanotechnology debates has been the embedding of responsible innovation principles into policy. The European Commission took a lead in this regard. In 2004, the EC's "*Towards a European Strategy for Nanotechnology*" communication explicitly stated that "*Nanotechnology must be developed in a safe and responsible manner. Ethical principles must be adhered to and potential health, safety or environmental risks [must be] scientifically studied… in order to prepare for possible regulation*." (European Commission, 2004). This marked a formal commitment to the precautionary principle in nanotech development. The EU followed up with a comprehensive *Nanotechnology Action Plan (2005–2009)* that integrated societal considerations (safety, environment, consumer protection) as key pillars. By 2008, the European Commission even adopted a Code of Conduct for

Responsible Nanosciences and Nanotechnologies Research built around seven principles such as sustainability, precaution, inclusiveness, and accountability (European Commission, 2008). These frameworks are usually considered to be amongst the earliest attempts to govern an emerging technology via soft law and ethical guidelines, and they have been widely cited as a model for RRI more broadly.

Several focal points defined the TA/STS debates on nanotech leading to tangible outcomes. First of which is the risk assessment of chemical toxicology of nanomaterials such as OECD's (still ongoing) work on Manufactured Nanomaterials[2] and EU's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) efforts on the topic (2007). The topic also expanded to cover other relevant aspects of manufacturing nanomaterials such as biodegradability, which again recently became a discussed topic following the increased use of nanofibers in masks during the COVID-19 pandemic (Trčka, et al., 2025).

Second tangible outcome is arguably the public engagement and transparency of discussions. Learning from earlier technological controversies (such as GMOs and nuclear power), policymakers and scholars treating nanotech advocated engaging the public upstream. Many countries experimented with citizen panels, consensus conferences, and stakeholder dialogues on nanotechnology's direction. In Europe, public dialogue was "*strongly encouraged*" as part of nanotech research policy (European Commission, 2004). Germany, for instance, supported a NanoDialog initiative and included civil society in discussions of its national nano action plans[3].

Finally, the nano debates helped institutionalize foresight activities where governments established formal programs to monitor and guide nanotechnology's development. In the U.S., the NNI incorporated a dedicated Societal Implications portfolio (Roco & Bainbridge, 2007), funding research in nano-ethics, law, and social impacts. In the EU, periodic reviews of the Nanotechnology Action Plan were conducted (with reports in 2007 and 2009 evaluating progress on safety, ethics, and public engagement). Germany launched inter-ministerial Nanotechnology Action Plans (2006, updated in 2011 and 2016) to coordinate R&D across eight ministries while pooling strategies for EHS[4]. This regular foresight approach, a form of institutional TA, kept attention on whether nanotech innovation was aligning with societal goals. It also led to course-corrections, such as increased funding for toxicity research when early studies indicated certain nanoparticles (such as carbon nanotubes) might pose asbestos-like risks.

Many concepts now central in technology policy, from precautionary measures, to ELSA research programs, to constructive technology assessment, were sharpened through the nanotechnology debates. By the 2010s, the lessons learned in the nano realm (the importance of integrating risk assessment early and maintaining public trust) were being actively transferred

[2] https://www.oecd.org/en/topics/nanomaterials-and-advanced-materials.html (Accessed 23 May 2025)
[3] https://www.bmuv.de/themen/chemikaliensicherheit/nanotechnologie/nanodialog (Accessed 23 May 2025)
[4] https://www.bmuv.de/en/topics/health-chemicals/overview-nanotechnology/german-government-nanotechnology-action-plans (Accessed 23 May 2025)

to newer domains like biotechnology and A.I., illustrating the crosscutting impact of TA/STS scholarship. Yet, the actual TA of the nano field appears to have reached a more established saturation point compared to A.I. debates (see Figure **C2.1.2**).

TA of Nuclear Technology

Nuclear technology has been a focal point for technology assessment and STS analysis since the Cold War era, providing some of the earliest examples of intense societal debate over technology's benefits and risks. After the first commercial nuclear reactors in the 1960s, optimism about cheap, abundant energy was soon tempered by public concerns regarding safety (e.g. the possibility of reactor accidents), radioactive waste disposal, and nuclear weapons proliferation. These concerns catalyzed formal TA activities; indeed, supporting nuclear decision-making was among the OTA's initial tasks. Throughout the 1970s and 1980s, OTA and other advisory bodies produced influential reports on issues like reactor safety and high-level waste management. For example, OTA's 1985 study "*Managing the Nation's High-Level Radioactive Waste*," (OTA, 1985b) which provided the U.S. Congress with options for long-term waste repositories. In parallel, a rich body of academic literature in TA and STS grew around nuclear power, examining how societies perceive and govern nuclear risks (Jasanoff & Kim, 2009; Grunwald, 2015; Jasanoff, 2022). By the late 20th century, nuclear energy governance had been significantly shaped by these assessments and insights, notably through stricter safety regulations, environmental impact requirements, and the recognition that public acceptance (or lack thereof) can make or break nuclear policy.

The issue of nuclear safety has been central in TA/STS debates, especially following high-profile accidents. The Three Mile Island accident (USA, 1979) and Chernobyl disaster (USSR, 1986) were watershed moments. They exposed the potentially catastrophic consequences of reactor failures and amplified public scrutiny worldwide. STS scholars like Charles Perrow argued that such accidents were "normal" – inevitable outcomes of tightly-coupled, complex systems like nuclear plants . Perrow's *Normal Accidents* (1984) highlighted how technical failures are intertwined with organizational and human factors. This insight spurred nuclear operators to adopt a more systemic approach to safety (e.g. creating the Institute of Nuclear Power Operations in the U.S. to institutionalize safety culture). Psychometric risk perception studies (Slovic, 1987) revealed that the public's dread of nuclear accidents far exceeded that of more familiar risks, challenging experts to bridge the perception gap. Meanwhile, Ulrich Beck's Risk Society (1992) thesis famously used nuclear disasters as examples of modern risks that transcend borders and elude full scientific control, thereby necessitating new democratic oversight mechanisms. These academic perspectives translated into concrete outcomes too. Nuclear regulators improved transparency and communication, emergency planning was overhauled, and international safety standards were continually strengthened (often under the IAEA and OECD Nuclear Energy Agency).

The challenge of safely managing nuclear waste for millennia, a scientifically and socially complex issue, is termed a "wicked problem". STS research illuminated how technical plans for repositories (like Yucca Mountain in the U.S. or deep geological storage in Europe) often floundered due to public opposition or ethical questions about imposing burdens on future

generations (Shrader-Frechette, 2000). In response, countries began adopting more participatory approaches in siting waste facilities. A notable outcome is the introduction of consensus-seeking and reversibility in waste programs: Sweden and Finland's repository projects, for instance, involved local communities from the start and offered veto rights – an approach informed by the idea that "decisions must be made in a stepwise, transparent way to earn social acceptability." International bodies like the OECD NEA held workshops on "Stakeholder Confidence in Radioactive Waste Disposal," concluding that sustained engagement is critical and that trust is not a given but must be continually earned (OECD NEA, 2017, p.30). This represents a shift from earlier top-down, technocratic decision-making to a more deliberative model, a shift strongly advocated by STS scholars.

Public perception and democratic governance debates were also prevalent in TA of nuclear technology. Public opposition movements have significantly influenced this technology's trajectory, from the environmental and antinuclear protests of the 1970s and 80s to the ongoing debates about nuclear's role in climate policy. TA and STS work has documented how public concerns often stem not from ignorance (as the old "deficit model" assumed) but from legitimate value differences and distrust in institutions. Jasanoff notes that "*The field of STS…, has evolved in close parallel with the nuclear energy field itself*" (2022), helping to shape discussions around what democratic control of such a high-stakes technology should look like. She contrasts a "technocratic" approach (favored by experts, focusing on quantitative risk assessments and cost-benefit calculations) with a "social-cultural" approach that asks "*how risks are recognized and why some are ignored*," examining history, framing, and cultural context (2022). Over time, elements of the latter approach entered policy: for example, many countries set up independent nuclear regulatory authorities to bolster credibility, and policy-makers began to consider ethical criteria (not just technical criteria) in decisions like whether to build new reactors. The German case is illustrative, public sentiment after Chernobyl and later Fukushima drove political decisions to halt nuclear energy, reflecting a societal risk calculus that went beyond what purely technical analysis would dictate.

A major outcome shaped by TA and social control of technology debates is the strengthening of international governance regimes for nuclear technology. Concerns about proliferation led to the Nuclear Non-Proliferation Treaty and a system of inspections; concerns about safety led to conventions on nuclear safety and waste management. The OECD's NEA and the EU's Euratom framework have increasingly incorporated social science research. These indicate an evolution of international and interdisciplinary oversight regimes that have formed in decades. The field has moved since the 1970s, it is no longer controversial to say that along with technical rigor, successful nuclear governance needs openness, public participation, and ethical reflection. Those principles can be considered as direct products of long-running STS and TA engagement with nuclear technology.

Across A.I., nanotechnology, and nuclear technology, the TA and STS debates, despite focusing on very different fields, converge on several common points. First, all three domains illustrate the Collingridge dilemma (1980; see Figure 7) early in a technology's life cycle, its risks and impacts are hard to predict, but by the time clearer knowledge emerges, the technology may be

deeply entrenched and difficult to change. This has led to a shared emphasis on “early warning” and proactive assessment. In practice, we see scenarios like the pre-emptive crafting of ethical guidelines for AI, the upfront funding of EHS research for nanomaterials, and the precautionary reactor designs in nuclear engineering, all attempts to anticipate and mitigate issues before they become crises. Second, the debates underscore the importance of governance frameworks that integrate ELSA considerations. In each domain, one of the main outcomes has been the formulation of guiding principles for responsible development. These frameworks reveal a common scientific insight, technological progress is not just a technical matter but also a values-driven process. TA and STS scholarship has been instrumental in formalizing those values (like, fairness in A.I., do-no-harm in nano, safety above all in nuclear) and embedding them into policy language. Third, public engagement and stakeholder involvement emerged as recurring themes. All three technologies experienced a legitimacy deficit when public concerns were ignored. The literature documents how opening up decision-making, whether through citizen panels on nanotech, public comment on AI deployments, or community consent in nuclear waste siting, tends to produce more robust and accepted outcomes. In each case, meaningful engagement is linked to building trust. A lack of trust can derail a technology (a clear example is the recent state of nuclear power in some countries), whereas trust enabled by transparency and dialogue can smooth implementation, like communities accepting nanotech in consumer products when given clear risk information. Thus, one scientific outcome is recognition of technology governance as an inherently democratic endeavor (Grunwald, 2019), echoing early TA proponents and STS scholars.

Another common point is the shift from reactive to adaptive, forward-looking governance. Historically, regulation often followed crises (like toughening of nuclear rules after accidents). TA/STS debates have pushed for more iterative and learning-oriented approaches, for instance, periodic review mechanisms, seen in the EU’s nanotech action plan (European Commission, 2004; 2008) and anticipated in A.I. regulations (European Union, 2024), as well as international forums to share lessons. All three domains now benefit from networks that continuously assess new developments: the Global Partnership on A.I. and OECD’s A.I. Policy Observatory for A.I.[5]; the International Dialogue on Responsible Nanotechnology via OECD/ISO for nano; and the IAEA/NEA peer review system for nuclear plants. These institutions embody the idea that governance must evolve with the science, a clear fruit of TA reasoning.

Finally, a unifying scientific outcome of these debates is a refined understanding of the sociotechnical nature of innovation. Technologies are not isolated artifacts; their success and impact depend on social contexts, cultural perceptions, and political choices. STS scholars often note that what differs across A.I., nanotech, and nuclear are the specifics, but what is common is that society shapes technology and vice versa. For example, the observation that different political cultures produce different “*imaginaries*” of nuclear power (Jasanoff and Kim, 2009) applies equally to how societies imagine A.I. (utopia vs. dystopia) or nanotech (revolutionary vs. risky). Thus, TA and STS debates have scientific merit in revealing patterns of co-production: how governance, public discourse, and technical trajectories co-evolve. A practical upshot is the widespread adoption of multi-disciplinary expertise in guiding technology, ethicists, social

[5] https://www.oecd.org/en/topics/sub-issues/ai-principles.html (Accessed 23 May 2025)

scientists, and public stakeholders now routinely join engineers and economists at the decision table for all three domains.

To sum up, it can be said that the half-century of experience since the OTA's founding has validated the core premise of TA; that systematic, inclusive examination of technology's consequences can improve decision-making. The debates in A.I., nanotechnology, and nuclear technology each (arguably) led to better-informed policies and a more nuanced collective understanding of those fields. As we face new challenges with emerging technologies (from biotechnology to quantum technologies), these hard-won insights, stressing anticipation, responsibility, and democratic governance, represent the main scientific outcomes of TA and STS debates, and they will remain essential for shaping a future in which technology and society progress together.

Structure of the thesis

This thesis is organized into three primary content chapters following this introductory section. The first chapter outlines **the landscape of quantum technologies,** offering a comprehensive overview of the ecosystem as of 2024, focusing on the **commercial, academic, technical, education, and geopolitical landscapes**. The second chapter introduces how responsible quantum technologies as a concept is taken into account in this thesis work, **the current state** of it, **how it is being studied and realized**, and some critical reactions to it from the quantum technologies community. Finally, chapter three synthesizes the highlighted points and discussions from the preceding chapters, **providing examples on how conditions in the current landscape can be related to the topics raised by (and against) the responsible quantum technologies discussions**. It concludes with a case example (quantum divide) on how the findings of this thesis can be utilized to develop strategic decisions by stakeholders on establishing conditions conducive to responsible futures in quantum technologies.

Methodology

There was a wide variety of research methods employed across the different parts of this thesis, integrating both quantitative and qualitative methods through four main data sources. The first source is bibliometric data from academic publications in quantum technologies, encompassing my own data collection and analysis, as well as work conducted by others, both prior to and concurrent with my research. The Scopus and Web of Science (WoS) access was provided through KIT. The search queries were formulated (when necessary) via utilizing previous studies, both mine (Seskir & Aydinoglu, 2021) and of others (Scheidsteger, et al., 2021, 2022; Liu, et al., 2022; Ichikawa, 2022; Gupta, et al., 2023). Only the numerical data (such as the number of articles per year from a country or on a topic or supported by a particular funding agency) was downloaded from the Scopus interface, and no complex network analysis was conducted.

The second source is patent literature in quantum technologies, accessed through assistive proprietary software (Cipher by Aistemos) and supplemented by analyses from existing studies

(e.g., those by JRC and EuroQuIC). When necessary, Espacenet[6] provided by the European Patent Office was also utilized. Access to the Cipher software was obtained via an agreement between Aistemos and Skoltech carried over to HHL Leipzig in 2022.

The third data source comprises gray literature, including policy reports, white papers, news articles, email newsletters, YouTube videos, and other non-peer-reviewed documents. These were mostly publicly available resources, with the primary exception of the utilization of Quantum Insider Data Platform in accordance with the agreement between KIT and Resonance.

The fourth data source consists of participant observation, gathered through my attendance at 45 onsite and five online events focused on QT, along with the 10 events I co-organized between December 2021 and April 2025, excluding panels, talks, and posters at STS and technology assessment events such as 4S, EASST, and ETAC. Although I took an active role in many of these events as speaker, panelist, or organizer, my note taking and observation approach aimed to follow the participant objectivation promoted by Bourdieu (2003). When mentioning or quoting, I anonymized the sources. The list of events can be found in Appendix A.

Limitations

There are some limitations that explicitly need to be acknowledged and kept in mind when reading this thesis, its arguments, findings, and conclusions. First of all, as described in the Prologue, my involvement in the field pre-dates this thesis work and goes beyond being just a technology assessment researcher. I care for the technology and I care for the community formed around the technology, and I wish for a global, inclusive, and cooperative development trajectory for it. This undoubtedly introduces a bias in my perception, which should be kept in mind when reading this work.

Second, again as highlighted in the prologue, the field is progressing rapidly and is being impacted by developments that are exogenous to its internal dynamics. If I were to carry out the work of this thesis between 2018-2021, some of my findings and recommendations would have been already out-of-date by now. Assuming this rapid progression is to continue, the findings of this thesis should be considered as a snapshot of the state of the field as of 2024 with some forward-looking projections which are subject to change due to internal and external causes.

The third limitation is related to geography and language. The datasets and secondary resources utilized for this study are mostly in English (and some in German), and are not truly exhaustive due to language barriers and secrecy, especially when it comes to (but not limited to) China. Due to increasing interest from the security stakeholders and potential military applications, the secrecy element is also becoming an issue that goes beyond China. Therefore, the data of this study is an incomplete collection, but it is representative and should be considered as such.

[6] https://worldwide.espacenet.com/patent/ (Accessed 23 May 2025)

Use of Generative A.I. Tools in the Thesis Work

I used ChatGPT for this thesis work mainly for editing and proofreading purposes. It was particularly useful in making the format of references coherent. I also used it for the generation of a few figures (Figures 7, **C1.4.1**, and **C1.4.2**) where I provided the input data and ChatGPT provided either the figures or the related Python codescript using matplotlib. No text was generated using ChatGPT or any other generative A.I. models.

Published Work and Their Contributions to the Thesis

In total, there are 14 academic publications that contributed to the content of this thesis work. There are 10 journal publications, two conference proceedings, and two book chapters.

The published articles, book chapters, and proceedings contributing to a chapter are listed at the end of that chapter in a table (Table **C1.6.1** for Chapter 1, Table **C2.4.1** for Chapter 2, and Table **C3.2.1** for Chapter 3). The complete "List of Publications Included in the Dissertation" in its short form is provided before the Table of Contents, and in its long form, with my contributions to each publication and the contribution of the publication to this thesis work, is provided below. The publications themselves in full form are provided in PART II of this manuscript.

1.1 (Article): "The landscape of the quantum start-up ecosystem" (Seskir, et al., 2022a)
Summary: This study examines the emergence and characteristics of QT start-ups, focusing on their temporal and geographical distribution, categorization, and growth patterns. Based on a dataset of 441 start-ups from 42 countries, the research highlights that over 92% were established in the last decade, with the majority based in the US, UK, and Canada. The start-ups are divided into six primary categories: complementary technologies, quantum computing (hardware and software), quantum cryptography/communication, quantum sensing and metrology, and support services. Findings suggest that countries with fewer QT start-ups may subsequently develop national initiatives, potentially driving an increase and diversification in QT start-up activities over time.

My contribution: I created the dataset of companies, categorized them, wrote the text, and developed the argumentation. My co-authors conducted the quantitative analysis and visualization and supported the development of the text and argumentation.

Contribution to Thesis Work: The dataset created for this study was later used in other papers and regularly updated. This study also served as a foundation for subsequent arguments, particularly those related to democratization, the quantum divide, and hype.

1.2 (Article): "Global innovation and competition in quantum technology, viewed through the lens of patents and artificial intelligence" (Seskir & Willoughby, 2023)
Summary: This study analyzes international trends in QT by leveraging a global patent database, developed using a hybrid approach that combines artificial intelligence and human expertise to define and analyze QT. The research underscores how AI-enhanced intellectual

property data can provide deeper insights into global innovation, benefiting policymakers and industry leaders beyond conventional data methods. The study also offers new perspectives on evolving QT sub-fields and highlights competitive dynamics, particularly between the USA and China, revealing key national and organizational profiles in the field.

My contribution: I developed the classifier using *Cipher*, an artificial intelligence tool provided by the company Aistemos. I wrote the text, conducted the analysis, generated the graphs, and crafted the argumentation. My co-author provided access to the proprietary software, assisted me in understanding the nuances and regional specifics of intellectual property laws and practices, and edited the text.

Contribution to thesis work: This work provided a solid foundation for arguments comparing the state of commercialization in the US and China, the evolution of global versus local markets for quantum technologies, and methods for tracking innovation in these emerging technology fields. Moreover, it enabled this thesis to move beyond a simple quantitative comparison of patent numbers across regions, offering a more qualitative understanding of what these patent numbers signify for different regions and markets.

1.3 (Book Chapter): "Subchapter 7.2.2: Milestones of research activity in quantum computing" (Seskir & Biamonte, 2024) in "Chapter 7: Physics for secure and efficient societies" in *EPS Grand Challenges – Physics for Society in the Horizon 2050*

Summary: This book chapter contends that quantum computing reached a significant turning point around 2017, driven by increased public and private investment and the integration of machine learning techniques. Machine learning began both simulating quantum systems and inspiring new quantum models, notably variational quantum computation. The authors outline key milestones leading to this shift and predict a future inflection point when quantum computers begin solving practical problems, potentially around 2050, a period when society will still be adapting to the transformative capabilities of quantum computing.

My contribution: I created the dataset, conducted the analysis, produced the visualizations, and wrote half of the text. My co-author contributed historical context to the analysis, wrote the other half of the text, and managed most of the communications with the book's editor and publisher.

Contribution to thesis work: This work provided valuable insights into how advancements in machine learning techniques spurred increased activity in quantum computing much earlier than typically acknowledged within the quantum technologies community. The positive impact of developing new machine learning techniques on quantum computing activity can be traced back to 2017, five years before the launch of ChatGPT. A limitation of this book chapter is that our contribution (titled *Milestones of Research Activity in Quantum Computing*) was merged with others' work in *Chapter 7: Physics for Secure and Efficient Societies*.

1.4 (Article): "Building a quantum-ready ecosystem" (Purohit, et al., 2024)

Summary: This paper addresses the rapid advancements in quantum technologies and their readiness for commercial application across various industries. It highlights the need for a "quantum-ready" ecosystem by introducing two frameworks: Quantum Technology Readiness Levels (QTRLs) and Quantum Commercial Readiness Levels (QCRLs), designed to assess both technological maturity and market viability. Additionally, it discusses the roles of key stakeholders—government, industry, and academia—and examines ethical and procedural considerations essential to building a robust quantum ecosystem. These frameworks and insights aim to facilitate a deeper understanding of the current status and future trajectory of quantum technology integration.

My contribution: I contributed data on start-ups, patents, and publications, assisted in the conceptualization of QTRLs, and supported the writing process.

Contribution to thesis work: This paper exemplifies how a widely used concept (readiness) in the quantum technologies domain can be further developed and operationalized for use by various stakeholders, particularly industry and government.

1.5 (Article): "Quantum games and interactive tools for quantum technologies outreach and education" (Seskir, et al., 2022b)

Summary: This paper provides a comprehensive overview of various quantum games and interactive tools developed for quantum education and outreach. Highlighted tools include "Hello Quantum," "Hello Qiskit," "Particle in a Box," "Psi and Delta," "QPlayLearn," "Virtual Lab by Quantum Flytrap," "Quantum Odyssey," "ScienceAtHome," and the "Virtual Quantum Optics Laboratory." Additionally, it discusses events like hackathons, game jams, and semester projects that support quantum game development, along with the Quantum Technologies Education for Everyone (QUTE4E) pilot project, which integrates these tools with educational efforts. The paper concludes with guidelines for embedding these games in educational materials to broaden access to quantum technologies.

My contribution: I conceptualized the initial idea, coordinated with the journal and guest editor for the special issue, assembled the author team, gathered their contributions, and developed most of the text. Various co-authors provided input for their respective sections, with some contributing further to writing, proofreading, and editing.

Contribution to thesis work: This work created a valuable resource for future efforts, both for myself and others. For instance, the exhibition *Ausstellung: Warum ist Quantenmechanik so wichtig beim Spielen?* (see Appendix A, Table **A1.3**) organized in Karlsruhe as part of the *Wissenschaftsreihe EFFEKTE* utilized some of the games discussed in this article. Additionally, it highlighted the potential of quantum games and interactive tools for educational and outreach purposes.

1.6 (Article): "A Chronicle of Quantum Technologies in Game and Software Development" (Skult, et al., 2024)

Summary: This paper examines the burgeoning field of quantum games, an innovative domain within quantum computing that applies quantum principles to game development. Despite the creation of over 300 quantum games by enthusiasts and commercial entities, a comprehensive review of the field is lacking. To address this, the paper provides an in-depth literature review, summarizing current advancements and notable examples of quantum games and interactive designs, and discusses future opportunities for integrating quantum technologies into game development.

My contribution: I assembled the author team, proposed the initial concept, communicated with the special issue editor, supervised the paper's development, and contributed to the writing.

Contribution to thesis work: This paper exemplifies how previous efforts in this thesis can be integrated. It builds upon arguments and insights developed in the papers *Quantum Games and Interactive Tools for Quantum Technologies Outreach and Education* (Seskir et al., 2022b) and *Communities of Quantum Technologies: Stakeholder Identification, Legitimation, and Interaction* (Umbrello et al., 2024) to explore how quantum technologies can be applied in game and software development. This work expands the practical use cases and stakeholder domains for quantum technologies into non-quantum fields.

1.7 (Article): "Educating to the "Culture" of Quantum Technologies: A Survey Study on Concepts for Public Awareness" (Seskir, et al., 2024b)

Summary: This article contributes to STEM education by examining essential concepts for QT outreach, using the discipline-culture (DC) framework to emphasize the importance of cultural nuances in QT education. A survey conducted by the QuTE4E pilot project explored key QT concepts, analyzing how these fit within or challenge traditional fields like Physics and Computer Science. Findings suggest that while core Quantum Mechanics concepts like the spin are valuable, they may need reevaluation in the context of QT outreach, where certain QT-specific ideas could take precedence. These insights are intended to guide educators in creating relevant and accessible QT outreach programs.

My contribution: I organized and conducted a survey titled *Quantum Outreach: Stakeholders, Opportunities, Problems, and Solutions* from December 2021 to June 2022 as part of the QUTE4E pilot project. For this paper, I analyzed a segment of the data generated from the survey (focusing on essential concepts for outreach), wrote the majority of the text, and managed communications with the journal. My co-authors contributed details and insights related to the discipline-culture framework, and assisted with writing and editing the manuscript.

Contribution to thesis work: This paper is one of the few to argue quantitatively for a deeper investigation into the disciplinary boundaries between quantum information science (QIS) and quantum physics. It also exemplifies the demarcation problem in defining quantum technologies, as although the term has historical precedence in the literature, it remains considerably vague.

1. 8 (Article): "Why teach quantum in your own time: the values of grassroots organizations involved in quantum technologies education and outreach" (Genenz, et al., 2025)

Summary: This paper explores the intersection of goals and values in grassroots organizations involved in QT education. It highlights a key distinction between the goal of providing education and the drive to democratize learning by prioritizing inclusivity, accessibility, and diversity. The analysis reveals how these organizations, in their early stages, navigate the dual challenge of staying true to foundational values while striving for sustainable growth in the specialized QT field. The study examines strategies such as creating educational ecosystems and fostering community engagement, and it discusses potential vulnerabilities, particularly regarding the longevity and evolution of these initiatives as members transition into professional roles in the quantum sector. This work provides a nuanced perspective on how emerging QT educational organizations balance ideological commitments with practical growth considerations.

My contribution: This paper was developed as an extension of a summer project I coordinated under QWorld's QIntern2023 program, titled *Exploration and Identification of Stakeholder Values in Quantum Technology* (QWorld, 2023). The project involved 14 interns from the quantum technologies community, who conducted interviews, focus group meetings, and a survey. Given that QIntern projects run from June to August, the project concluded with only preliminary findings. Later, Ulrike Genenz took over the coordination and writing of the paper during her internship at ITAS for her M.Sc. degree at RWTH Aachen, with support from Adrian Schmidt, another colleague at ITAS. I assumed a more supervisory role, providing input when needed, contributing some of the text, and performing editing work.

Contribution to thesis work: This work demonstrates how a specific group of stakeholders can be mapped and examined regarding their values and roles within the quantum technologies ecosystem. The outcomes of this project, and subsequently the paper, were presented at various venues and discussed with relevant actors from the quantum technologies education and outreach communities. Given that grassroots organizations in quantum technologies remain an underexplored group of stakeholders and research subjects, even within the education and outreach research, this study addresses a critical gap in the literature.

1.9 (Conference Proceeding): "Games for Quantum Physics Education" (Chiofalo, et al., 2024)

Summary: This conference paper argues that public education in quantum mechanics, crucial in the era of the second quantum revolution, represents both a challenge and an opportunity to enhance cultural literacy. Despite the complexity and counterintuitive nature of quantum theory, the authors propose that games can serve as an engaging, accessible platform to foster "quantum literacy," allowing individuals to explore quantum principles creatively and experimentally. The paper outlines theoretical foundations for integrating games into a global educational strategy, reviews current applications across educational and citizen-science contexts, and discusses future challenges in broadening access to quantum learning.

My contribution: I coordinated a project under QWorld's QIntern2021 program titled *Mapping the Landscape of Quantum Games* (QWorld, 2021). This project involved seven interns who conducted mapping exercises using publicly available resources to compile a comprehensive list of quantum games accessible at that time. Given that QIntern projects span June to August, this project concluded with only preliminary findings. I later leveraged the data gathered from this summer project, with support from colleagues in the QUTE4E pilot project, and contributed to this conference paper.

Contribution to thesis work: This work exemplifies how quantum games can serve educational purposes and potentially contribute to citizen-science initiatives.

1.10 (Book Chapter): "Communicating Quantum Technologies in an Era of Mistrust and Misinformation" (Goorney, et al., 2024a)

Summary: This book chapter presents the QuTE4E project, a community-driven initiative aimed at increasing public awareness of QT through structured outreach. Originating from a network of over 400 educators, academics, and industry experts across 45 countries, QuTE4E worked within the broader European QTEdu initiative, launching 11 pilot projects targeting diverse audiences, including the public, industry, and educational institutions. QuTE4E emphasizes public communication of QT through a research-based approach called Physics Outreach Research (POR). The project seeks to foster a quantum-literate society, crucial for both workforce development and informed policy-making. A Delphi Study informed the project's outreach strategy, which culminated in the culturo-scientific storytelling (CSS) framework—a narrative approach designed to effectively communicate QT concepts. The paper concludes with insights on outreach effectiveness and the importance of RRI in public awareness efforts.

My contribution: As noted for Paper 1.7, within the QUTE4E project, we conducted a survey on quantum outreach. For this book chapter, I analyzed and applied the responses from the survey's "Challenges" section. Additionally, I supported the operationalization of certain RRI principles in the context of quantum outreach.

Contribution to thesis work: This book chapter serves as a summary and narrative of the various activities conducted under the QUTE4E project, which I co-coordinated. It addresses a critical discussion within the quantum technologies ecosystem, how to introduce these technologies to the public. Given that a substantial portion of the QUTE4E community comprises physicists and educators (including education researchers), this chapter advocates for and provides guidance on introducing quantum technologies in a careful, ethical, and respectful manner.

1.11 (Conference Proceeding): "Exploring Pitfalls for Defence and Security by Narratives on Quantum Technologies" (Seskir, et al., 2024a)

Summary: This paper explores the influence of three prevalent narratives—quantum computing as a threat, quantum mechanics as incomprehensible, and quantum technologies as a geopolitical battleground—on the development of quantum technologies for defense and security. The authors argue that these narratives create pitfalls: threat inflation, which may result

in hasty policy decisions; decision-makers disengaging due to the perceived complexity of quantum mechanics; and overprotectionism, which could stifle international collaboration. The paper advocates for a critical examination of these narratives to encourage a balanced perspective, enabling more thoughtful and effective policy-making in defense and security applications of quantum technologies.

My contribution: Building on insights from the democratization paper (Seskir et al., 2023a), I conceptualized the work, wrote the majority of the text, submitted the proposal, and later presented the paper at the symposium.

Contribution to thesis work: This work serves as an example of stakeholder-specific conceptual exploration, focused on defense and security stakeholders. It demonstrates how operationalizing relevant concepts can foster opportunities for dialogue and reflection within and across stakeholder communities.

2.1 (Article): "Democratization of quantum technologies" (Seskir, et al., 2023a)

Summary: This paper examines the concept of democratization in QT, particularly in quantum computing, by analyzing how various democratic theories (participatory, representative, and deliberative) apply to QT. It identifies that democratization, often framed narrowly in the industry, is primarily led by companies focusing on quantum computing. The authors review narratives and counter-narratives around QT democratization and discuss broader efforts, including accessible technologies, grassroots communities, and manifesto development. Ultimately, they argue that while these efforts are vital first steps, they are not sufficient for true democratization. The paper calls for increased reflexivity and transparency within QT initiatives to better align with democratic values, potentially resulting in QT advancements that serve society more effectively.

My contribution: I initiated the work, supported the operationalization of certain concepts, coordinated the writing process, and authored most of the text. My co-authors developed the conceptual and operational framework, contributed to the literature review, crafted parts of the argumentation, and provided proofreading and editing.

Contribution to thesis work: This paper was pivotal to the thesis, as it offered a well-structured example of how a widely used concept within the quantum ecosystem (*democratization*, in this case) can be further developed and operationalized for application by various stakeholders in the field, particularly ELSA researchers focused on quantum technologies, as well as education and outreach providers.

2.2 (Article): "Communities of quantum technologies: Stakeholder identification, legitimation and interaction" (Umbrello, et al., 2024)

Summary: This paper explores stakeholder identification in QT through the lens of value-sensitive design (VSD), offering insights into QT's complex and evolving landscape. It provides two detailed lists of stakeholders, including entities such as private firms, government bodies, NGOs, and trade organizations, to guide VSD researchers and practitioners. The lists

aim to support ethical and responsible QT development by clarifying stakeholder roles and interactions. They also provide a basis for policy and strategy formulation and enable empirical and technical studies on QT innovations within an ethics-driven framework like VSD.

My contribution: I created two datasets (Seskir et al., 2023b; 2023c), which serve as the quantitative foundation for this study and are publicly available on the Zenodo platform. I also conducted the literature review and contributed to writing and editing the text.

Contribution to thesis work: This paper exemplifies moving beyond reductionist stakeholder mapping approaches that depend on the quadruple helix model (Carayannis & Campbell, 2009). Additionally, it provides a foundational dataset for future stakeholder mapping efforts, which we later leveraged to map grassroots initiatives (Genenz et al., 2025).

3.1 (Article): "Navigating the Quantum Divide(s)" (Gercek & Seskir, 2025)

Summary: This article examines multiple "quantum divides" that may emerge as QT develops, moving beyond the idea of a singular divide. Four key divides are identified: (1) a scientific divide, reflecting disparities in scientific access and knowledge within the research community; (2) a technological divide influenced by path dependency in technology adoption; (3) a geopolitical divide, highlighting differing motivations and outcomes for QT adoption between countries at various development stages; and (4) a societal divide, focusing on QT's broader societal impacts. The study underscores the interconnected nature of these divides and suggests strategies for mitigating their effects, providing insights for stakeholders interested in navigating QT's impact on scientific, technological, geopolitical, and social frameworks.

My contribution: My co-author, a KIT Aspiring Grant (Doc) recipient, was a visiting researcher at ITAS for four weeks in October 2023. I developed the idea and primary concepts, while she drafted most of the initial text. We then collaborated closely on all aspects of the paper, making this an equal-contribution effort (as acknowledged in the publication).

Contribution to thesis work: This paper illustrates a potential policy-oriented outcome of this thesis by identifying possible emerging quantum divides and proposing managerial actions and policy recommendations to address these divides and mitigate their most adverse potential impact.

Chapter 1: Landscaping of the Quantum Technologies Ecosystem(s)

The landscape of quantum technologies has been evolving quickly in the last decade, especially since 2016 when IBM (Vu, 2016) opened up their first accessible quantum computer on cloud and the Quantum Manifesto (De Touzalin, et al., 2016) was published in Europe. This chapter focuses on landscaping the current state of these technologies on the commercial, academic, technical, educational, and geopolitical fronts.

1.1 The Commercial Landscape of Quantum Technologies

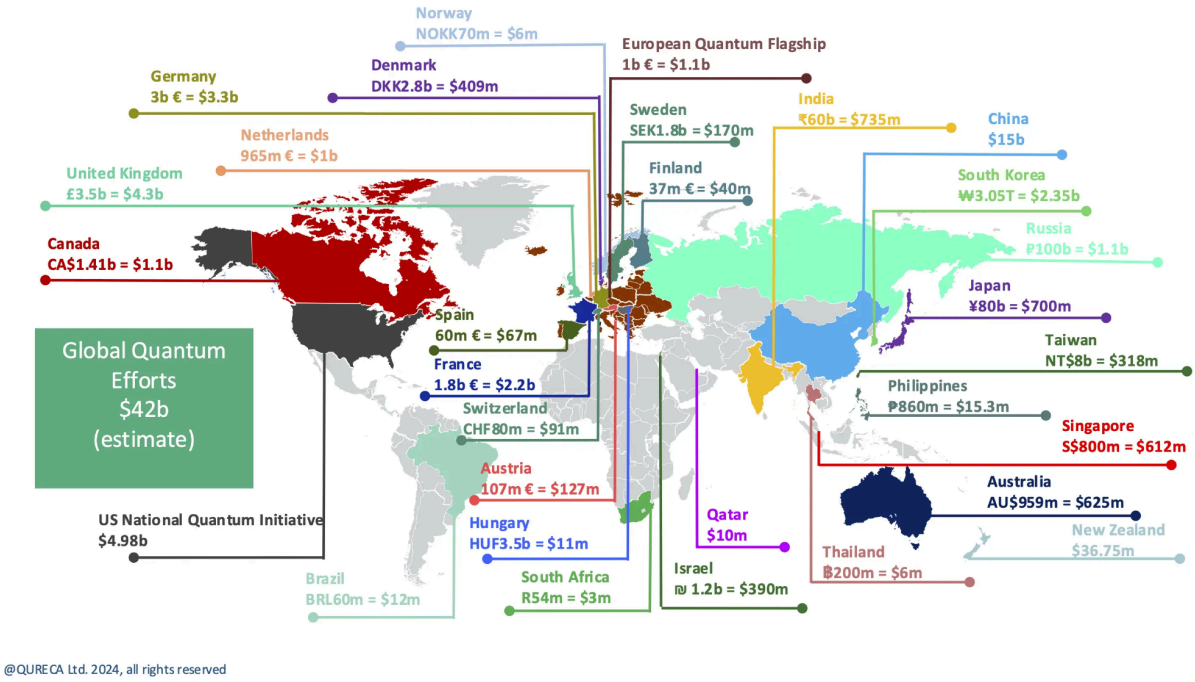


Figure **C1.1.1**: A summary of the programs and efforts around the world (QURECA, 2024)

The yearly global quantum efforts update by the company QURECA has been a major source and used widely by the community to keep track of government initiatives and investment into the field. As it can be seen from Figure **C1.1.1**, there are tens of public initiatives with promised investment amounts ranging from $3M to $15B. These are total estimated amounts, for context and as an example, the European Quantum Flagship is a 10-year long program. Similarly, the US National Quantum Initiative, which is depicted in the figure with an almost $5B investment amount, is a 5+5 year program. Several others, like the UK and Germany, are also compiling different funding amounts and schemes together. Yet, other than the amount stated for China, there is little doubt on the accuracy of these numbers (for detailed explanation on each entry, check the relevant QURECA webpage[7]).

[7] https://www.qureca.com/quantum-initiatives-worldwide/ (Accessed 23 May 2025)

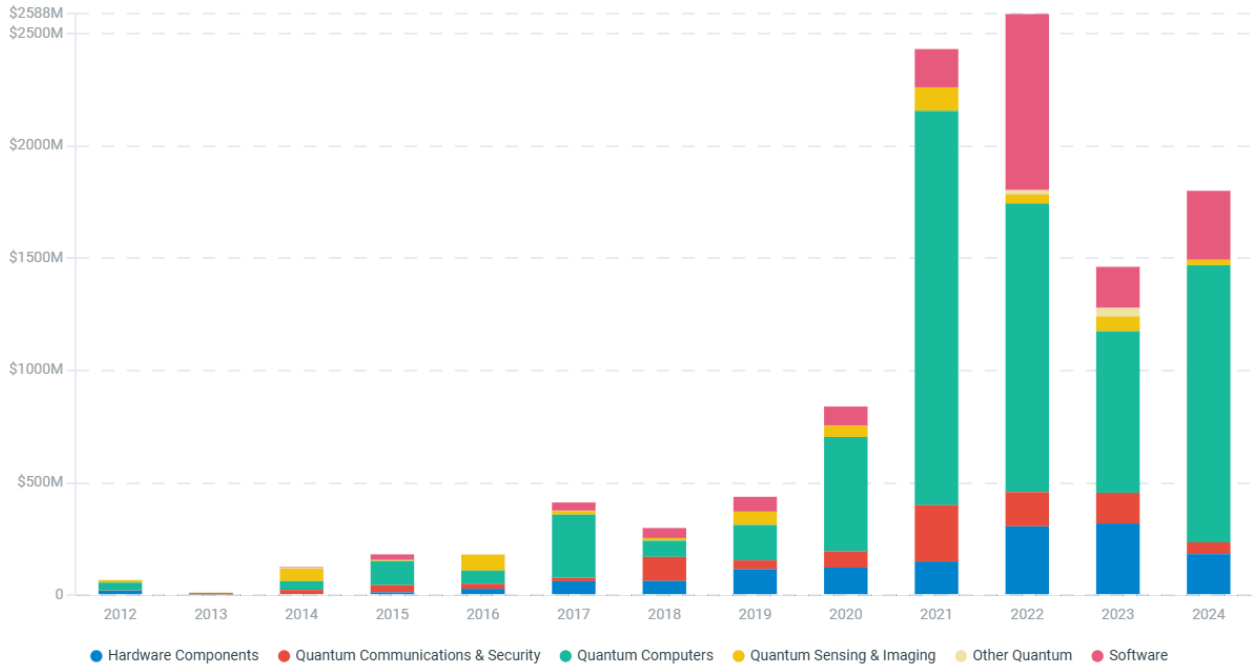


Figure **C1.1.2**: Funding rounds (by $ amount) per year on different subcategories of QT

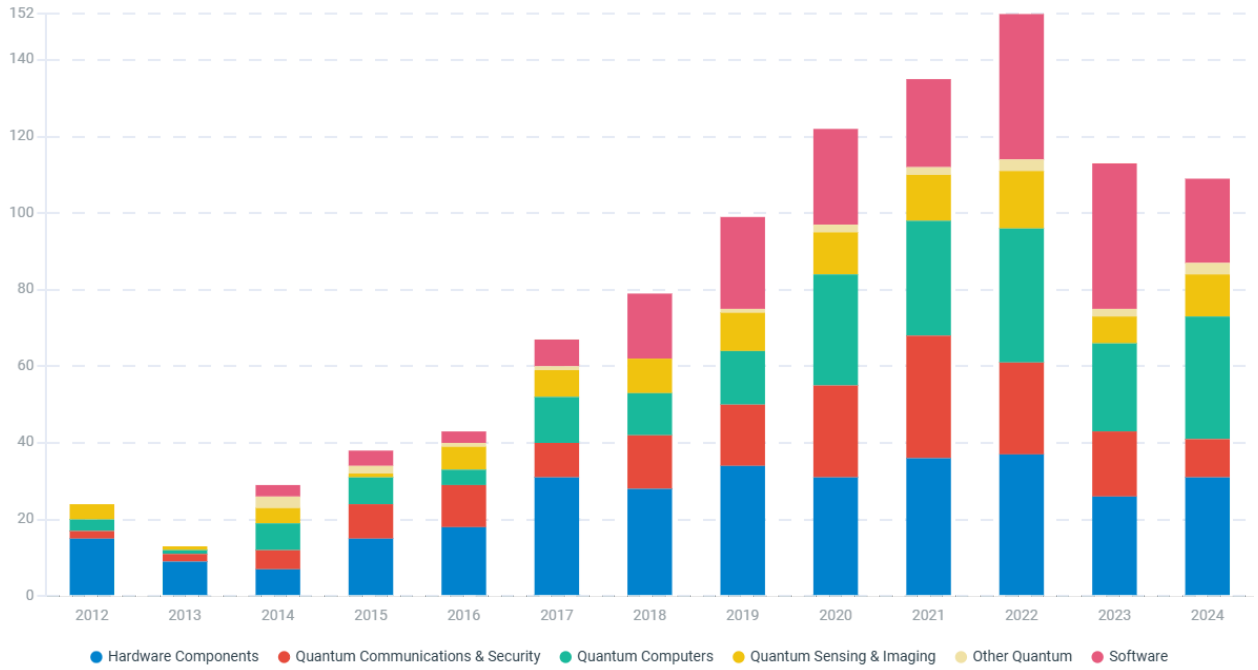


Figure **C1.1.3**: Funding rounds (by # of rounds) per year on different subcategories of QT

As investment by the public sources is usually mentioned as the main funding source of the field, it is harder to estimate the amount of private investment going into it. For this, I utilized two resources. First is the data obtained from the Quantum Insider Data Platform (see Methodology) on funding rounds (by $ amounts and # of rounds), which are presented in Figures **C1.1.2** and **C1.1.3**. Second is the data presented at McKinsey's yearly *Quantum Technology Monitor*

published in April 2024 (Bogobowicz, et al., 2024), which states higher numbers, $2.35B for 2022 and $1.71B for 2023 (p.11), yet the trend of growth until 2022 and a noticeable decline in 2023 persists in both sources. The McKinsey report also states that the ratio of public investment into the companies compared to private investment has been growing steadily from 10% in 2021 and 20% in 2022 to 32% in 2023 (p.15).

The reason I try to use multiple data sources comes from the fact that different data sources report different numbers. For example, the *Quantum Technology Monitor* mentioned above reports a total of 380 quantum start-ups founded between 2001 and 2023 (p.16), yet they state it is a non-exhaustive listing. This makes sense, as my own research and reporting for the landscape of quantum start-ups (Seskir, et al., 2022a) came up with 441 companies as of early 2022. Later, I continued updating the dataset I compiled for that article and as of May 2024, I had 563 companies listed on it. A graph I created using the updated dataset for a Flagship Coordination Office presentation in May 2024 depicting the number of new quantum start-ups founded per year is provided in **Figure C1.1.4**.

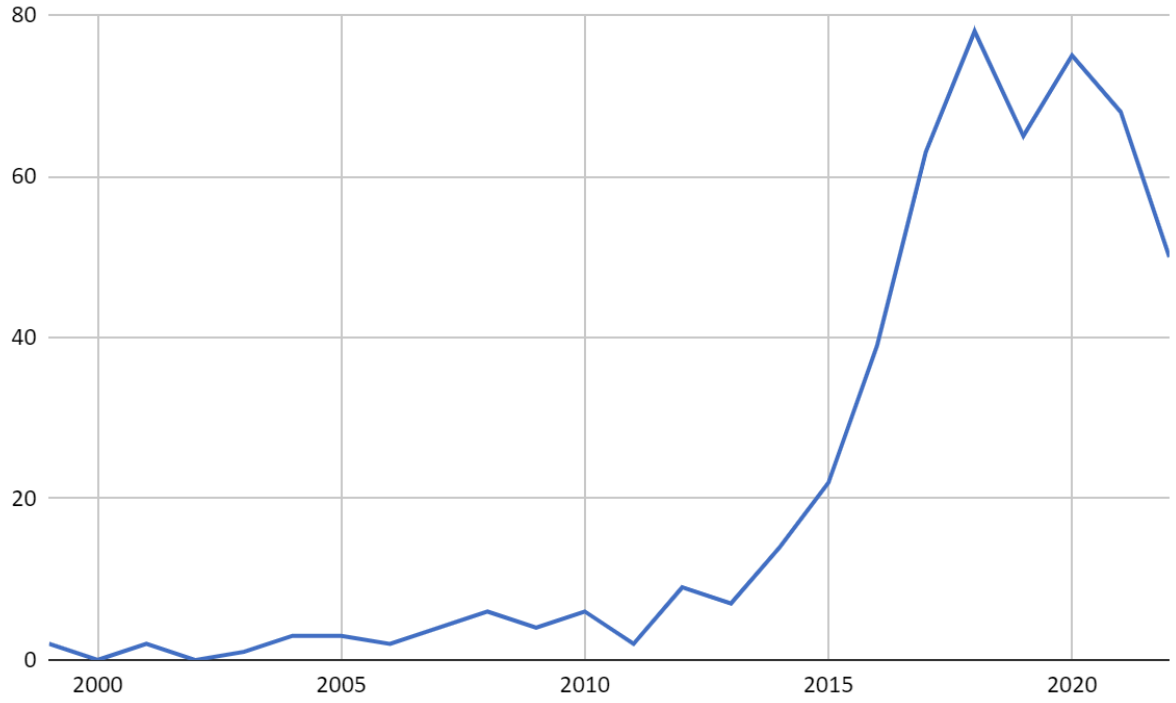


Figure **C1.1.4**: Number of new quantum start-ups founded per year (an updated version of Seskir, et al. 2022a)

Beyond the analysis of focusing on start-ups or new companies, it is quite difficult to find a complete list of commercial actors. I tried creating one using the patent analysis study (Seskir & Willoughby, 2023) I conducted, yet it yielded no fruit. Not every commercial actor involved in these technologies file for patents and not every company that filed patents in this domain actually conducts commercial activities. For this aspect, I returned again to the Quantum Insider Data Platform which contains more than 1300 companies involved in quantum technologies.

First, I looked at the distribution of companies in countries with more than 10 companies listed in the dataset, as I had experience in this distribution from my previous study (see Figure 2 on the article Seskir, et al., 2022a). After confirming that the distribution fits to my findings (see Figure **C1.1.5**), I continued with further analysis of the 1367 companies listed on the dataset.

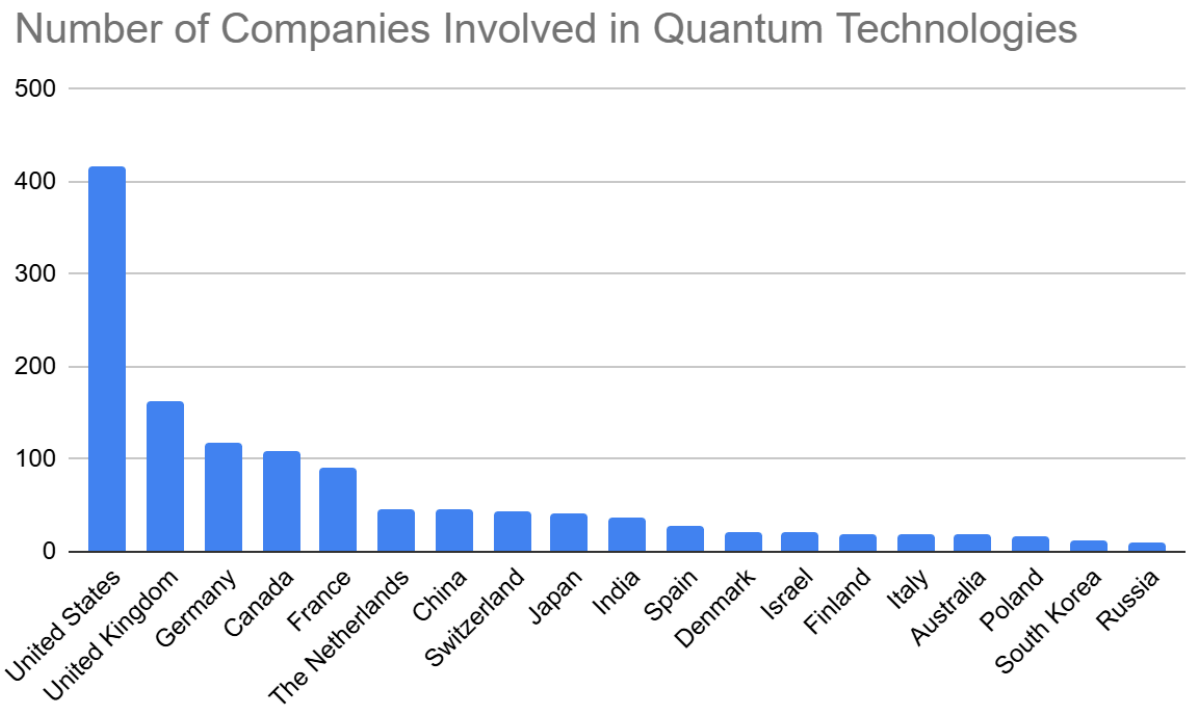


Figure **C1.1.5**: Number of companies involved in quantum technologies by country

One particularly useful visualization for myself that I developed was the heatmap on Figure **C1.1.6** on the number of companies in each country. Given that the United States had 416 companies while even its closest followers (UK and Germany) had much less (162 and 117 respectively) made this visualization challenging. Yet the resulting map reveals that the United States is by far the most active country commercially if we take the countries as the relevant unit of analysis for such comparison. This result also fits the findings of the patent landscape analysis (Seskir & Willoughby, 2023) conducted for this thesis, which revealed that although the sheer number of patents in China has surpassed the United States, the patent analysis very clearly reveals that commercial actors expect the first real market for quantum technologies to be in the United States and the Chinese efforts are more on the defensive side (to protect their domestic markets) rather than the expansionist side (trying to leverage their domestic R&D to penetrate and gain a foothold in foreign markets).

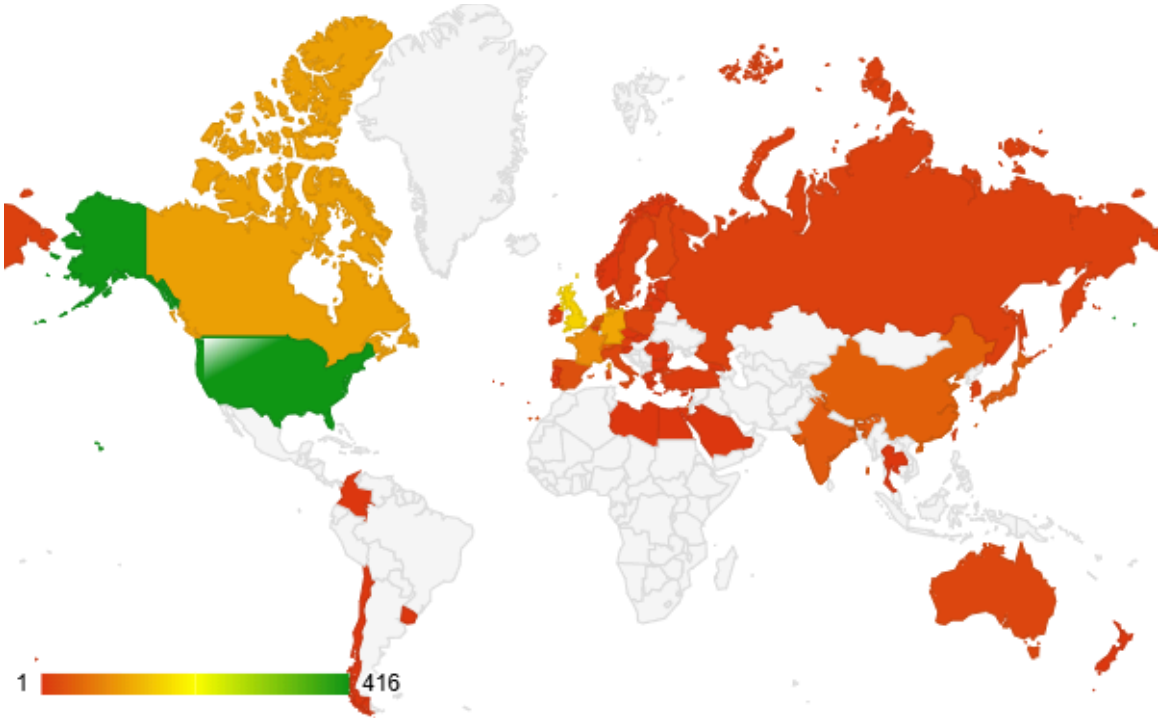


Figure **C1.1.6**: Heatmap of companies involved in quantum technologies by countries

The reason I mentioned the issue of relevant units of analysis is that if we switch from a country level analysis to a clustered or regional comparison, the picture starts to change. This was actually thanks to the suggestion of a reviewer for the start-ups study (Seskir, et al., 2022a) who advised us to include a US vs. EU comparison.

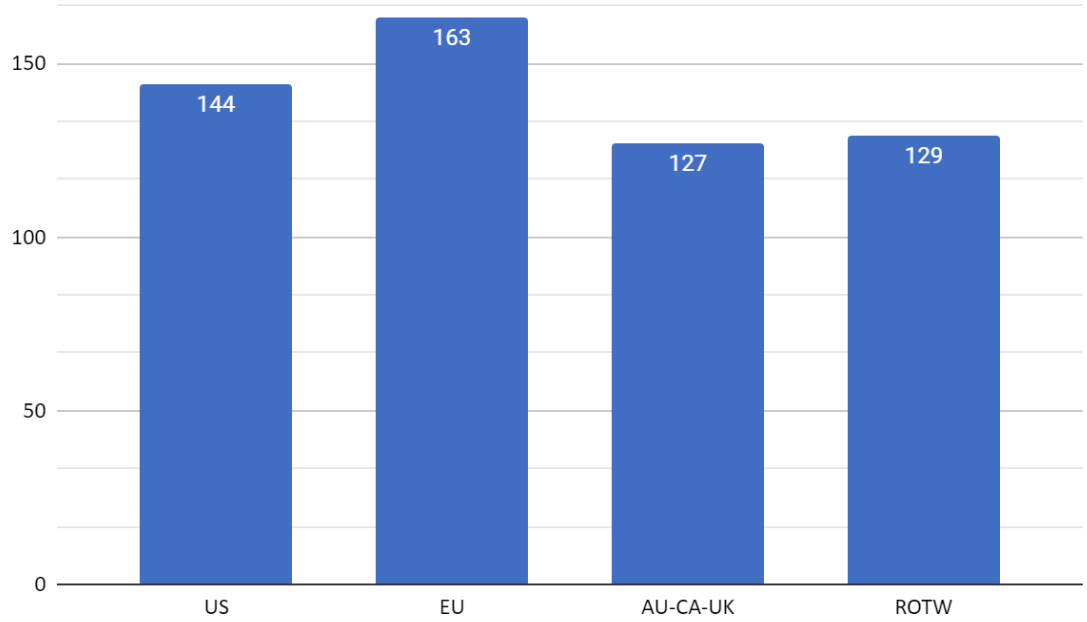


Figure **C1.1.7**: Number of quantum start-ups founded by cluster (an updated version of Seskir, et al. 2022a)

The initial analysis for the paper revealed a lucky coincidence, that when we conducted the initial analysis (early 2022), the number of start-ups founded in my dataset in the United States and the European Union member states (EU-27) were exactly the same, 121 in both cases (out of 441 in total). After two years, I ran the analysis again for the new dataset of 563 start-ups, which revealed that the EU27 has overtaken the US by quite a margin.

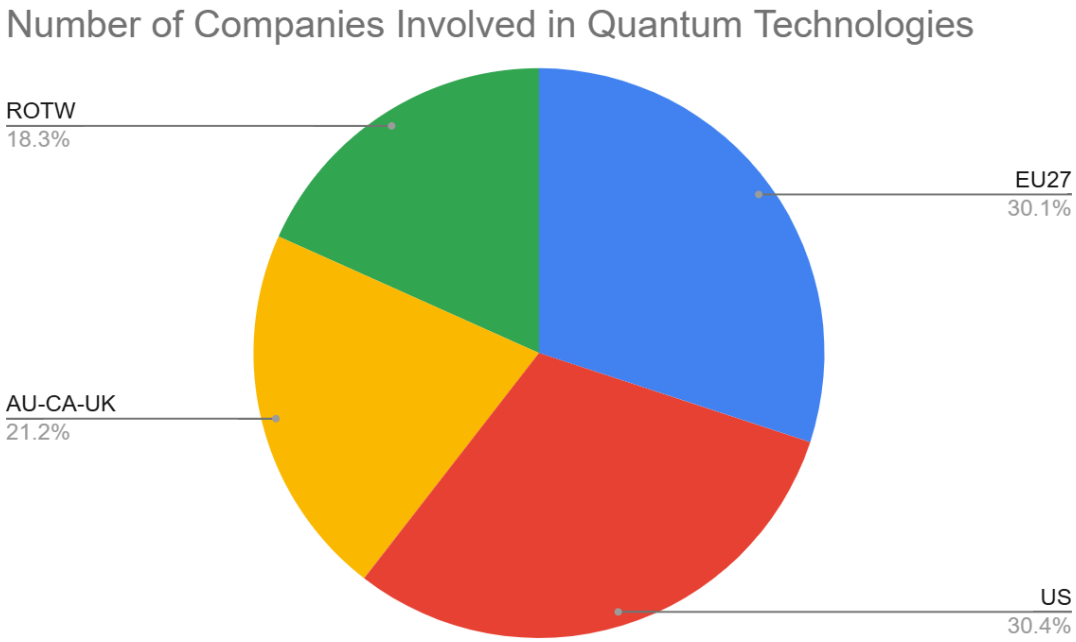


Figure **C1.1.8**: Number of companies involved in quantum technologies (clustered analysis)

To compare my own dataset of start-ups with the overall number of companies involved in quantum technologies listed in the Quantum Insider Data Platform, I ran the same clustered comparison there as well, for the 1367 companies covered (see Figure **C1.1.8**). The results were quite similar, yet the number of companies involved in the US was a bit higher than EU27. This would actually indicate that although the number of start-ups in the US stopped growing as rapidly as they are in the EU, non-quantum companies getting involved in the field did not suffer a similar setback.

At this point, both for completeness sake and to add an additional dimension to the analysis at hand, I utilized the employee range information provided in the platform. This information was available on a regional level, where the regions were given as Europe, the Middle East and Africa (EMEA), Americas, and Asia–Pacific (APAC). The resulting graph can be seen in Figure **C1.1.9**. It shows that although the number of small and medium enterprises (SMEs) involved in quantum technologies is higher in EMEA, for considerably large enterprises (1000+ employees) involved in quantum technologies, Americas is the leading region.

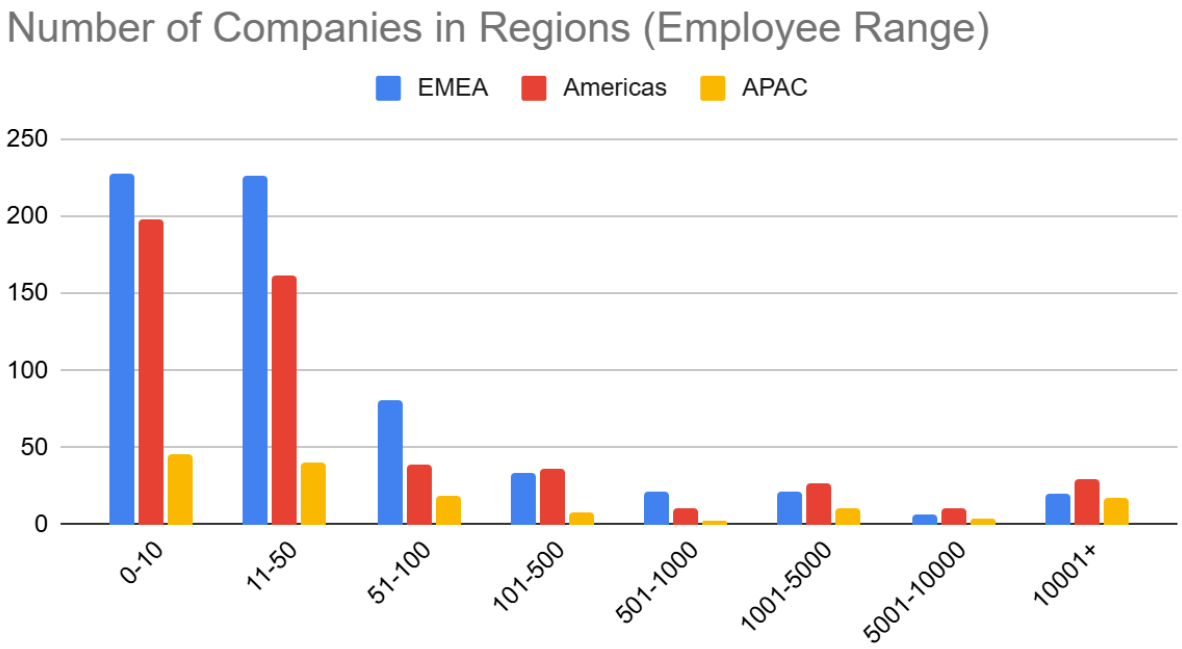


Figure **C1.1.9**: Number of companies involved in quantum technologies in different regions with respect to their employee ranges

Before concluding this subsection, there is a need to address the relative decline from 2022 to 2023 in Figures **C1.1.2, C1.1.3,** and **C.1.1.4**. There are many different reasons, but I will emphasize the changes occurred in the investment landscape. First, as mentioned in the prologue, the launch of ChatGPT had an immense impact on the technology investment landscape. According to the *Quantum Technology Monitor* report (p.14) the investments into GenAI grew from $19B in 2022 to $48B in 2023. All this investment hike had to come from somewhere. At the same time, as a secondary impact, both FED and the ECB started increasing their interest rates in 2022 following the start of Russian invasion of Ukraine which added a further set of shocks to an already fragile global economy following the pandemic era. Raising interest rates effectively makes available money more valuable, hence decreasing the amount of investment, which can be clearly seen as according to Crunchbase the global startup investment in 2023 was only $285B, marking a 38% decline over $462B in 2022 (Teare, 2024). 38% is almost exactly the same amount of decline in investments into quantum technologies between 2022 and 2023 according to Figure **C1.1.2**, indicating that quantum technologies didn't underperform as an emerging technology, nor did they overperform like generative AI.

Combining all these information on public and private investments, temporal and geographical distribution of start-ups and involved companies, the type of companies active in different regions, together with the findings from publications 1.1 on start-ups (Seskir, et al., 2022a) and 1.2 on patents (Seskir & Willoughby, 2023), and the impact of developments in 2022, there are several points to be highlighted for this thesis work. First, although the United States as a country has a clear lead if we stick to a country level analysis, this picture disappears quickly when the unit of analysis is replaced with a cluster of countries or regions. Second, although

there is still a comparative competition between the regions of what is usually referred to as the Global North, the same cannot be said for between the Global North and the Global South (see Figure **C1.1.6**). Third, although the number of companies and developers of these technologies in different regions of the Global North is still in flux and there isn't a clear lead yet, looking at the patenting activity trends (Seskir & Willoughby, 2023), the type of companies involved in quantum technologies (Figure **C1.1.9**), and the ratio of private investments (45% for EU vs. 87% for the US according to the *Quantum Technology Monitor* report, p.19), it is not difficult to ascertain that the initial primary market for these technologies will be the United States. Finally, although there is quite an interest in quantum technologies, it is not in the same category of A.I. which seems to defy market dynamics. Quantum technologies, for better or worse, are subject to the changes in market dynamics, the available amount of investment, different prioritization of countries, and so on. Even if they are perceived as strategic, from a commercial perspective, they are not different from regular emerging technology.

These four points related to the commercial landscape of quantum technologies; (i) a clear lead of the United States as a country vs. ongoing competition in Global North as regions, (ii) clear gap between the Global North and Global South, (iii) United States as the initial primary market, and (iv) quantum technologies being subject to regular market forces have clear ramifications on identifying the critical junctures for different futures, which will be revisited at the end of this chapter and in Chapter 3.

1.2 The Academic Landscape of Quantum Technologies

In this part of Chapter 1 on landscaping of the quantum technologies ecosystems, I provide data and analysis on the academic landscape of the field. There is already a relatively extensive literature on bibliometric analysis of the field in total (Seskir & Aydinoglu, 2021; Scheidsteger, et al., 2021), its history (Scheidsteger, et al., 2022), and different areas of it such as quantum communication (Liu, et al., 2022), quantum sensing (Gupta, et al., 2023), quantum computation and algorithms research (Ichikawa, 2022), and even niche topics like quantum machine learning (Pande & Mulay, 2020), which I also contributed via the publication 1.3 (Seskir & Biamonte, 2024). Therefore, instead of reproducing an updated version of these bibliometric mapping and analysis, I will focus more on not the content of the academic landscape (i.e. keywords, co-citation, and bibliographic coupling analysis), but more on how different countries and regions fare against each other and how the funding landscape has evolved in the last 25 years.

I used Web of Science as my main data source for the first part of this landscaping exercise, utilizing the keywords obtained from previous literature, primarily my own publications (Seskir & Aydinoglu, 2021; Seskir & Biamonte, 2024). The final search query (see **Appendix A3**) was run in November 2024 and resulted in 91,591 results and 86,772 after the results were refined to only include article type documents (excluding only book chapters, proceedings, data papers which did not result in published articles). One quirk of WoS is that it does not cluster the UK automatically as a country, instead it provides results separately for England, Scotland, Wales, and North Ireland. Keeping this in mind, countries with top20 publications are listed in Figure **C1.2.1**.

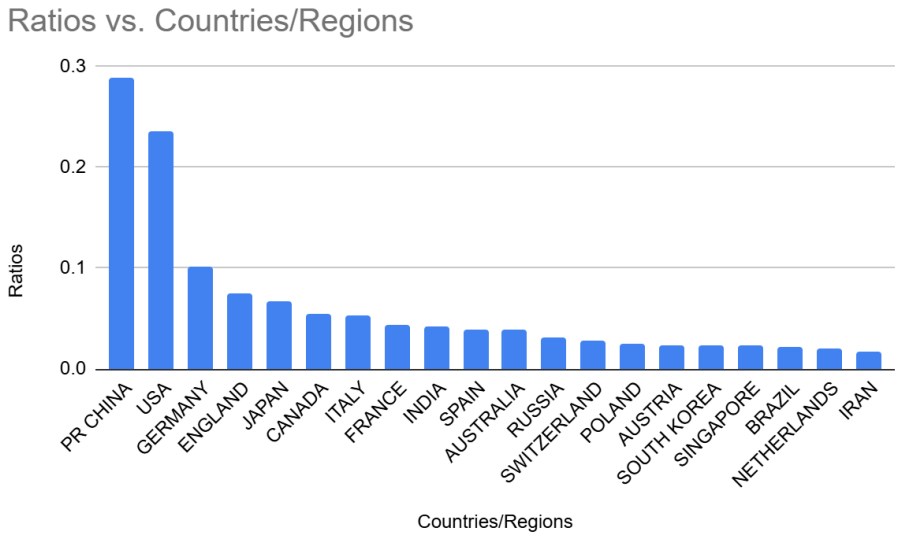


Figure **C1.2.1**: # of publications from a Country/Region divided by # of total publications

This figure shows that almost 29% of all publications in the field had at least one author with Chinese affiliation, 24% had US affiliation, 10% had German affiliation, and when England, Scotland, Wales, and North Ireland combined, they had around 9%. Hence, from an academic publication perspective, the top4 countries are PRC, USA, Germany, and the UK.

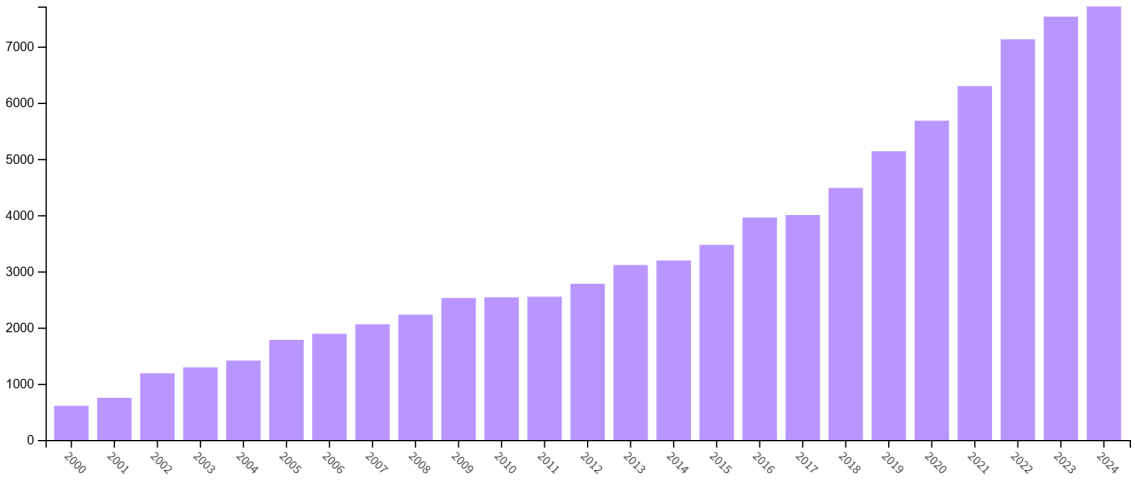


Figure **C1.2.2**: # of publications per year in the dataset for the last 25 years

The next item I checked was the number of new publications per year, especially to see whether the drop in investment is represented in any way. Figure **C1.2.2** shows that the field has been growing steadily for the last 25 years, growing from 600 articles per year in 2000 to 8000 articles in 2024, a 13-fold increase. In comparison to A.I. (see Figure 1), the growth is relatively weak given that A.I. grew from around 2000 publications in 2000 to more than 70000 publications in 2021, a 35-fold increase. Similarly, nanotechnology publications grew from around 600 in 2000

to around 20000 in 2024, a 33-fold increase. Given these numbers, and the almost linear increase of new articles per year in Figure **C1.2.2**, compared to the almost exponential growth in A.I. publications in Figure 1, this again hints us that comparing A.I. and quantum technologies is not a correct comparison. Similar to having different investment and market dynamics, they also have different publication dynamics. Quantum technologies as a field, for better or worse, does not resemble the A.I. field.



Figure **C1.2.3**: Top10 funding agencies appearing in the publication acknowledgement sections

Following this, I moved on to identifying the funding sources of the academic research conducted in the field (Figue **C1.2.3**). Not surprisingly, they were from China, the US, the EU, the UK, Germany, and Japan, as it can be guessed from looking at Figure **C1.2.1**. As usual, funding and publication numbers go hand in hand.

Next, I moved to analyze whether any country or region listed above has lost appetite for these technologies in terms of research. For the UK, I combined England, Scotland, Wales, and North Ireland. For the EU, I combined all EU-27 member countries (excluding the UK). I divided the publication numbers each year by the total number of published articles from a country. For example, there were 1707 publications with at least one author with a US affiliation in 2023, given that the total number of publications in the dataset from the US is 20,510, this corresponds to 8.3% of publications in quantum technologies out of the US were published in 2023. This analysis would reveal, even if the sheer number of publications in a country is high, interest there might be falling. Yet, Figure **C1.2.4** shows that this is not the case, and in all four of the regions and countries in question, the ratio of publication has been growing steadily in the last 25 years.

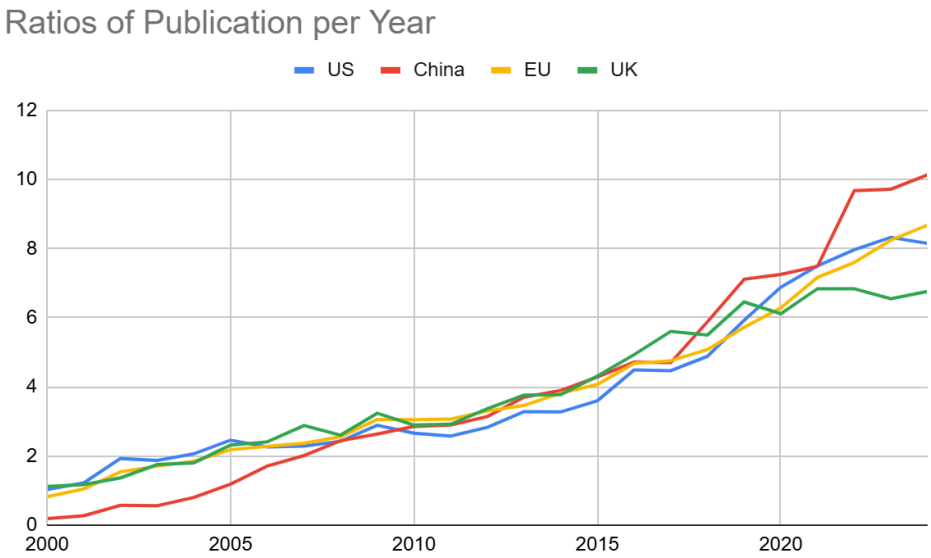


Figure **C1.2.4**: Ratios of publications per year by major players with respect to their total publications since 2000

As the next step, I tried to ascertain some further characteristics of the funding activities carried out by NSFC, NSF, DoD, EU (which is an umbrella term used for framework programme funding such as FP7, H2020, and Horizon Europe, not including distinct funding lines such as ERC or Marie Curie), and UKRI. First, I looked at the ratio of funded research versus total publications coming out of a country or region.

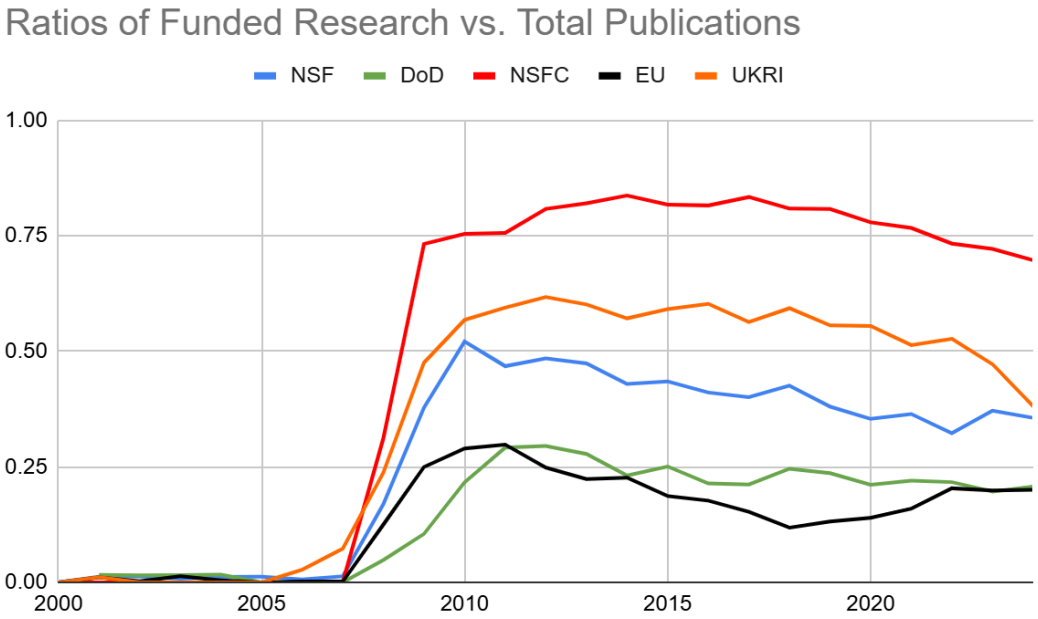


Figure **C1.2.5**: Ratios of research funding by NSF, DoD, NSFC, EU, and UKRI from respective countries or regions

This data is not easy to come by, therefore I assume the WoS database lacks a clear way to keep track of funding data before 2009. Looking at the data post-2009 (Figure **C1.2.5**), the ratios appear to be quite stable for the following 15 years except UKRI and NSF. Yet it can be seen from the data that different countries and regions have very different approaches to funding research into this field. For example, NSFC with a budget of $5B (2024) out of China's total budget of $52B on science and technology (Mallapaty, 2024), either partially or fully funds three quarters of research on quantum technologies coming out of China. Meanwhile, NSF with a total budget of $9B (2024) out of the total $27B US science funding (Tollefson, 2023), funds around one-third of the quantum technologies research coming out of the US.

A more interesting data point for this work was whether these funding agencies co-fund joint research activities. To account for that, I restricted my datasets to only research articles funded by each agency and ran the funding agency analysis for each of them, which led to the creation of Table **C1.2.1**.

Table **C1.2.1**: Co-funded research ratios between top5 funding agencies of QT research

	NSF	*DoD*	*NSFC*	*EU*	*UKRI*
NSF	6369 (**100%**)	1781 (**48%**)	309 (**2%**)	220 (**5%**)	194 (**6%**)
DoD	1781 (**28%**)	3675 (**100%**)	154 (**1%**)	244 (**6%**)	169 (**5%**)
NSFC	309 (**5%**)	154 (**4%**)	17618 (**100%**)	152 (**4%**)	151 (**5%**)
EU	220 (**3%**)	244 (**7%**)	152 (**1%**)	4255 (**100%**)	555 (**17%**)
UKRI	194 (**3%**)	169 (**5%**)	151 (**1%**)	555 (**13%**)	3348 (**100%**)

This reveals three crucial points about the research funding of quantum technologies. First, there is relatively little cross-regional collaboration and co-funding, except in the case of EU and UK, which is historically expected as the UK was a part of EU funding schemes until 2016. Second, China is especially isolationist in terms of its funded research activities in quantum technologies, where NSF is the only non-Chinese co-funding source in the top25 of NSFC funded research (which from Figure **C1.2.4** we know that corresponds to around three quarters of entire Chinese research activities in quantum technologies). In comparison, NSF has eight non-US funding agencies listed within its top25 co-funding organizations: NSFC (China), NSERC (Canada), ERC (Europe), EU (Europe), DFG (Germany), UKRI (UK), MEXT (Japan), and JSPS (Japan). Even DoD has EU, NSERC, UKRI, ERC, EPSRC (UK), NSFC, DFG, and SNSF (Switzerland) on its list. Third, is the close relations between NSF and DoD, where DoD co-funding appears on 28% of NSF funded research, and NSF co-funding appears on 48% of DoD funded research, which highlights the close relationship between the US defence research and science funding mechanisms.

Establishing the limited amount of co-funding of research activities between regions, I wanted to explore whether this accurately represents the lack of collaboration between different regions.

Table **C1.2.2**: Academic co-publication ratios between China, the US, and EU-27 regions

	China	*US*	*EU-27*
China	25103 (**100%**)	1994 (**10%**)	1978 (**7%**)
US	1994 (**8%**)	20510 (**100%**)	4232 (**16%**)
EU-27	1978 (**8%**)	4232 (**20%**)	26597 (**100%**)

Table **C1.2.2** paints a similar picture to Table **C1.2.1** but in less severe terms. For example, more than 20% of research with at least one author with US affiliations also has at least one author with EU-27 affiliation. Similarly, even for the relatively isolationist China in terms of research funding, there were joint publications with US and EU-27 affiliated researchers at 8% each. To figure out whether these correspond to very large and overlapping collaboration networks, I restricted the search to cover only research with authors covering all three (China, US, and EU-27), which resulted in 313 articles. This is around 1% for each of the regions, hence indicating that a total of 15% of research with at least one author in China had collaboration with authors either in the US or EU-27.

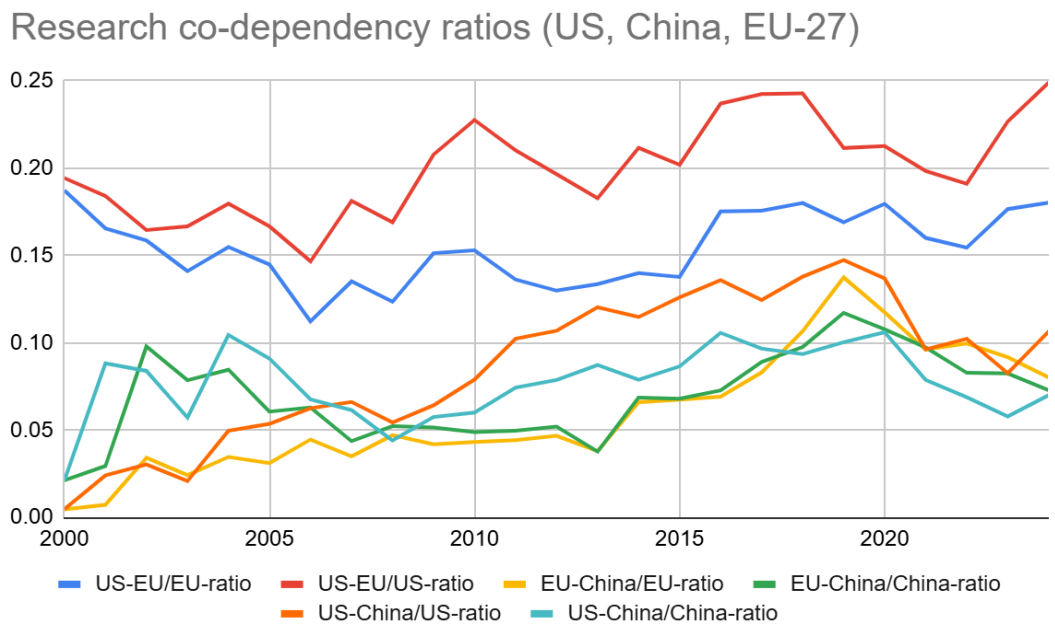


Figure **C1.2.6**: Ratios of research-dependencies between US, China, and EU-27

This brought up an interesting question, who depended on whom more in terms of collaboration. To identify this, I downloaded the datasets containing the number of publications per year of US, China, and EU-27 separately, and also the US-China, US-EU, and EU-China joint publications. Combining all and representing them in ratios spread over the last 25 years resulted in Figure **C1.2.6**. This figure reveals three points. First, the US dependency for research in quantum technologies is higher compared to the EU dependency on the US. Second, both researchers from the US and the EU had been increasing their collaboration with researchers located in

China steadily since 2000 until 2019 where the ratios for both shrink by around one third. Finally, the interdependencies between the US and the EU research ecosystems in quantum technologies have always been stronger compared to the US-China and EU-China research collaboration relations.

When the number of publications in quantum technologies with respect to countries, the sources of funding for academic research in the field and the co-funding activities of different agencies, together with co-publication and research dependency ratios between major regions (i.e. China, US, EU-27) combined, there are three points to highlight for this thesis work. First, quantum technologies are neither A.I. nor nanotechnology in terms of its publications dynamics. New number of publications in the field of A.I. grew exponentially in the recent years (Figure 1), while the new number of publications using the keyword "nanotech*" peaked in 2020 and has been declining since then. In contrast to these two, the number of new publications in quantum technologies have been steadily increasing in the last 25 years (see Figure **C1.2.2**) and the ratios of publication each year by major players in the field have been increasing steadily as well (see Figure **C1.2.4**).

The second point is the clear presence and high level of academic activity coming out of China and different funding approaches between regions. Figure **C1.2.1** shows that almost 30% of all academic publications in the field have at least one author with Chinese affiliations, while Figure **C1.2.3** shows that the number of academic publications citing the National Natural Science Foundation of China (NSFC) as their funding source is equal to the NSF, EU, DoD, and UKRI supported ones combined. Yet Figure **C1.2.5** showing the ratios of research funding by top funding agencies in different regions might tell a different story, where the Chinese academic publications heavily rely on NSFC funding (almost 80% cite NSFC as one of their funding source), these ratios are quite lower in other regions and countries, indicating a variety and diversity of funding sources. Finally, the ratios of co-funding between top funding agencies (see Table **C1.2.1**), combined with co-publication ratios between the respective regions (see Table **C1.2.2**), and their research co-dependency ratios (see Figure **C1.2.6**) hint that although research in quantum technologies is sometimes argued to be highly international, this is not apparent in neither co-funding activities nor co-publication ratios. The highest codependency is the US dependency on US-EU joint publications with 25%, and that the Chinese dependency on research collaboration with both EU and US is already under 10%.

These three points; (i) quantum technologies having a steady increase in new publications for the last 25 years, unlike the A.I. or nanotechnology, (ii) China having a strong presence in the academic publication and a centralized funding approach compared to other regions, and (iii) relative lack of co-funding activities by top funding agencies between regions and the way research codependency dynamics are evolving, are relevant for this study and will be highlighted again at the end of this chapter and in Chapter 3 when interconnections for responsible quantum technologies are being discussed.

1.3 The Technical Landscape of Quantum Technologies

Providing a technical landscape of quantum technologies similar to the one provided above for academic and commercial landscapes is not a straightforward task, especially given that quantum computing, quantum sensing, and quantum networking are different technologies.

In his last book, *Schrödinger's Web: Race to Build the Quantum Internet* (2020), Jonathan Dowling provides an argument that quantum networks, especially the repeaters in those networks, can be formulated and thought about as small quantum computers since they will consist of qubits, which in time will also be able to perform quantum circuit operations. He makes a similar argument for quantum sensing as well:

"*It may seem a bit odd that quantum sensors are considered part of quantum information science, but there is a reason for that. Way back in February of 1998, I gave the first public talk on quantum sensors, "From Quantum Computers to Quantum Gyroscopes," at the NASA International Conference on Quantum Computing & Quantum Communications, in Palm Springs, California. I had been scheduled to give a talk on another topic, and my time slot was in the morning on Friday of the last day. I never gave my planned talk. Instead, after listening to the other presentations all week, I had one of my most profound ideas – a quantum sensor is a special-purpose quantum computer!*" (Dowling, 2020, p. 223)

Hence, as there are widely differing technical details and requirements coming from domain specific constraints, the most important question for any type of quantum technologies is how the mathematical concept of a qubit is physically realized.

Quantum technologies, especially quantum computing, employ various qubit modalities, each with unique strengths and challenges:

- Superconducting qubits, built using superconducting circuits to create quantized energy levels, have gained popularity due to their compatibility with semiconductor fabrication techniques (Devoret & Schoelkopf, 2013). Companies like IBM, Google, and Rigetti are advancing this technology to scale quantum systems (Arute et al., 2019).

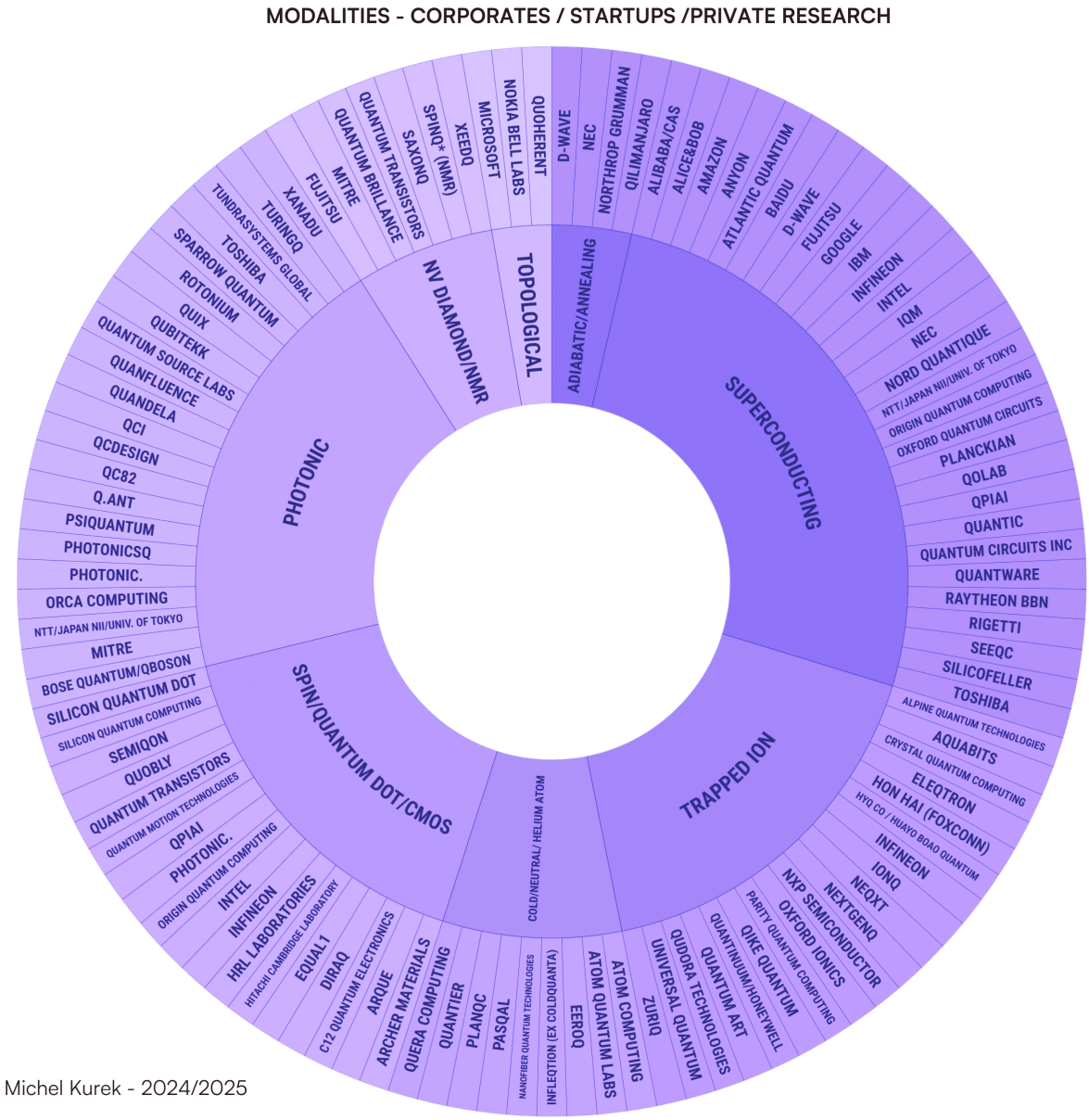
- Trapped ion qubits use ions held in place by electromagnetic fields and manipulated with lasers. Known for their long coherence times and high operational fidelity, this approach is championed by companies such as IonQ and Quantinuum (Monroe et al., 2014; Debnath et al., 2016).

- Neutral atom qubits, employing atoms like rubidium-87 (Rb-87), are another emerging modality. These atoms are cooled, trapped in programmable arrays using optical tweezers, and manipulated via Rydberg interactions, offering scalability and reconfigurable architectures (Saffman et al., 2010; Henriet et al., 2020). Companies like QuEra are advancing this technology for quantum computing and simulation.

- Topological qubits, which rely on the exotic properties of topological matter, aim to improve fault tolerance, though they remain experimental (Kitaev, 2003).

- Photonic qubits, which use the quantum properties of light, are still in early development but hold promise for scalable quantum communication and computation (Knill et al., 2001). Companies like PsiQuantum and Xanadu are pursuing this approach.

Other modalities include NV centers in diamond, which leverage optically addressable spin states for quantum computing and sensing, thanks to their long coherence times and magnetic field sensitivity (Doherty et al., 2013). Lastly, silicon spin qubits, based on the spin states of electrons or nuclei in silicon quantum dots, offer compatibility with silicon manufacturing and high qubit density (Veldhorst et al., 2014), with companies like Intel driving their development. Yet, all these technologies have different maturity levels, which can be described by the Quantum Technology Readiness Levels (QTRL) approach (Purohit, et al., 2024).



Michel Kurek - 2024/2025

Figure **C1.3.1**: Research on different qubit modalities by private actors as of late 2024

There is constant change and progress in most of the qubit modalities even on a monthly basis. Furthermore, as these different modalities have varying and sometimes incompatible specs (in terms of qubit fidelity, coherence times, error types, etc.), there is an entire community forming focusing just on how to compare the performances of these different types of physical hardware modalities. A good example of this is https://metriq.info/, which is a community-driven quantum benchmarks platform supported by Unitary Fund, a 501(c)(3) non-profit "helping create a quantum technology ecosystem that benefits the most people" according to their website.

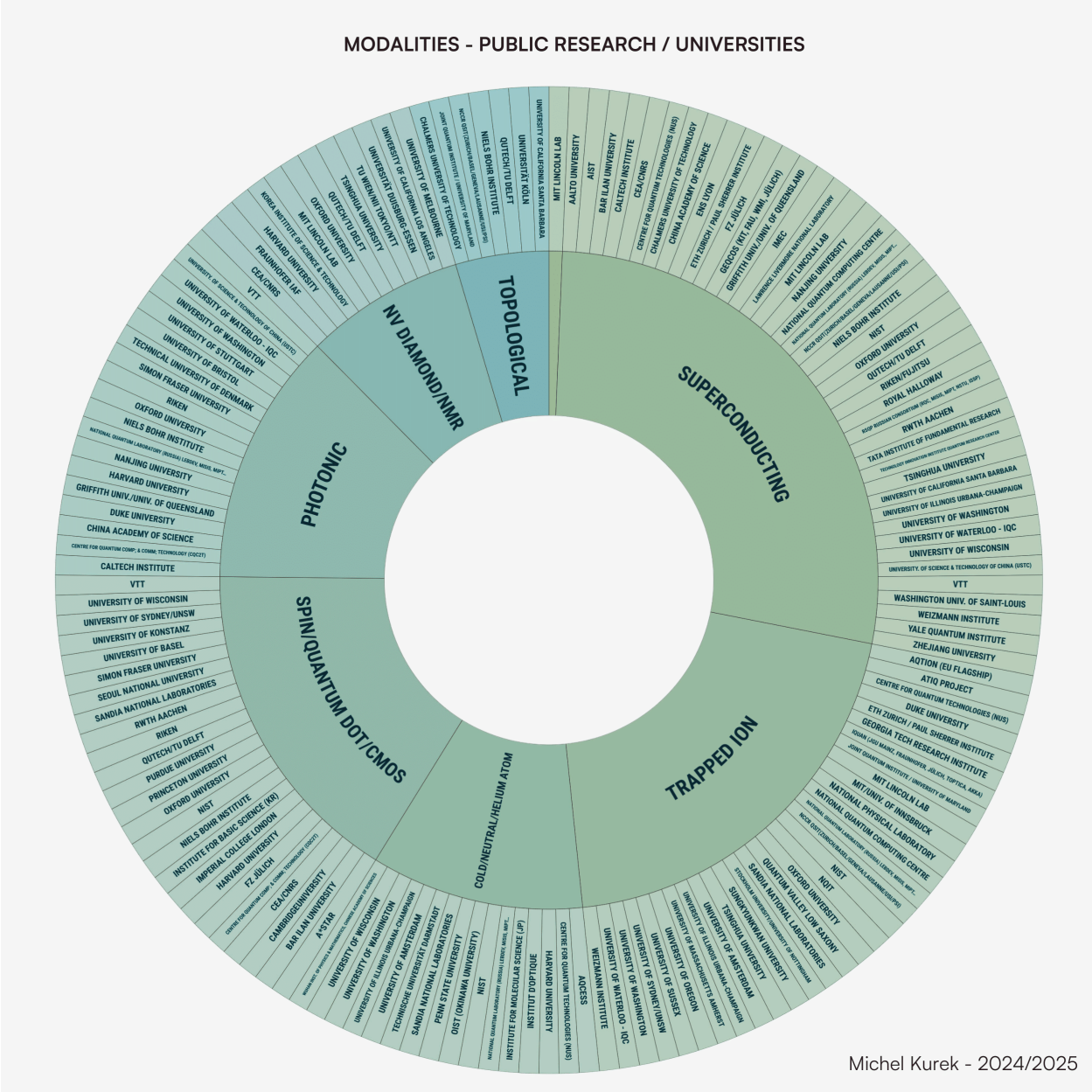


Figure **C1.3.2**: Research on different qubit modalities by public actors as of late 2024

Organizations like McKinsey and BCG publish yearly reports on quantum technologies, such as the *Quantum Technology Monitor* (Bogobowicz, et al., 2024) utilized in previous subsections.

However, when it comes to keeping track of the landscape of hardware modalities, it is not easy. There are two figures provided by Michel Kurek, who has been publishing updated versions of these qubit wheels since the last several years (Kurek, 2020). Figures **C1.3.1** and **C1.3.2** show that there are at least seven major research lines focusing on exploring how to physically realize qubits for quantum computation purposes. I am not aware of any for topological qubits, but for the other six (superconducting, trapped ions, cold/neutral atoms, spin/quantum dots, photonic qubits, and NV centers), there are ongoing corresponding research activities for developing quantum sensing and quantum networking devices using these technologies.

This level of diversity in terms of exploring different research lines for physical realization of qubits is a topic considered important by many in the community as I encountered quite frequently during my participant observations. For example, whenever the question of "what if XYZ company fails to deliver their promise on time" is asked (which is asked mostly about either for big tech. players like IBM and Google, or strongly present but controversial start-ups likes PsiQuantum and IonQ), the regular reply usually follows arguing that even if some of the research lines (say, photonic or superconducting) leads to dead-ends or halted progress, the field of quantum technologies is diverse enough in terms of its research base to adapt to that. It is a very practical example of how the concept of diversity is called upon to argue for the resilience of a technology development ecosystem in the face of potential failures.

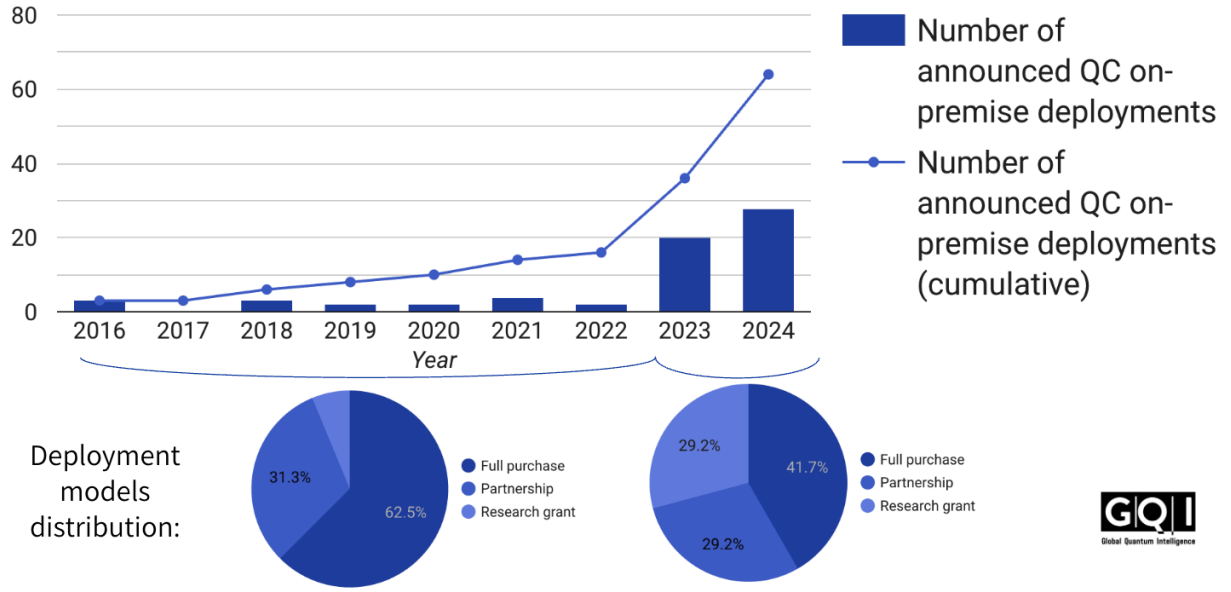


Figure **C1.3.3**: Evolution of quantum computing on-premise deployments from 2016 to 2024 (Quantum Computing Report, 2024)

The question of on-premise vs. cloud in terms of how quantum computers will be utilized when they become commercially relevant has also been a highly relevant question since early days. Companies like IBM, Microsoft, and Amazon started providing cloud access to quantum hardware devices through their already established cloud platforms, IBM Quantum, Microsoft Azure Quantum, and Amazon Braket. Yet starting from 2022 the number of announced

on-premise quantum computer deployments increased quite rapidly in 2023, and this trend appeared to be continuing in 2024 and possibly extending to 2025 (Quantum Computing Report, 2024), which can be seen on Figure **C1.3.3**.

One can speculate on the reasons, yet two things are clear. First, a considerable number of the new on-premise procurements are done through research grants, hence these are not commercial purchases but primarily public ones. This is not necessarily surprising, given that the date coincides with the aftermath of Russian invasion of Ukraine and the increasing perceived importance of quantum technologies for defence (Seskir, et al., 2024a), and that we saw in the last two years a progress towards some indication of overprotectionism towards even practically useless quantum computers via export controls from countries like the UK, the US, and others (Titcomb, 2024; Zhang, 2024).

The second point is that it is not only one or two private actors becoming hyper-active and selling a host of quantum computers. It is known that IonQ sold devices to Air Force Research Lab in the US (Quantum Zeitgeist, 2023) and QuantumBasel in Switzerland (Swayne, 2024), IBM sold devices to RIKEN in Japan and Cleveland Clinic in the US (IBM Newsroom, 2024), and Rigetti sold devices to the Superconducting Quantum Materials and Systems Center led by Fermilab in the US, and Horizon Quantum Computing based in Singapore (Rigetti Computing, 2024). There is also the European Quantum Computing & Simulation Infrastructure (EuroQCS) which was announced in 2022 (Binosi, et al., 2022; European Commission, 2022), and is in the process which is resulting in purchasing of six quantum computers that will be located at sites in Czechia, Germany, Spain, France, Italy, and Poland. These are sourced from different European companies such as IQM, AQT, Pasqal, and others. Hence, for quantum computers there are a multitude of buyers and multitude of sellers, utilizing at least two different hardware modality approaches, superconducting quantum circuits and ion traps. For quantum technologies other than computing, such as sensing and communications, coming up with such figures is a harder challenge. Yet, there are major activities in those fields as well.

The European Quantum Communication Infrastructure (EuroQCI) is a good example to be followed closely (see Figure **C1.3.4**). The PETRUS CSA of EuroQCI is coordinating the national QCIs of the EU-27 countries, which all have signed the EuroQCI declaration. As part of this grand initiative, all EU-27 countries will be connected to each other through QKD networks. EuroQCI is planned to be used only for government communications, yet there are already six industrial QKD projects promoted on the PETRUS website, and the OpenQKD consortium, which initially ran a project of the same name between 2019-2023, developed more than 30 use cases[8] for QKD systems.

[8] https://openqkd.eu/openqkd-in-action/ (Accessed 23 May 2025)



Figure **C1.3.4**: National EuroQCI logos. Source: PETRUS[9]

China has a strong foothold in quantum communications as well. Dowling describes in his book that this was not an expected outcome by the experts in the US:

"*My government told me that "The U.S. is always at least ten years ahead of its adversaries – the Chinese quantum satellite is merely a propaganda ploy that will blow up on the launchpad." I tried!*
The Chinese launched the quantum satellite Mozi in August of 2016 – and it did not blow up – surprise! Instead the spacecraft worked extremely well – better than even the Chinese expected – and it began to take scientific data by January of 2017. In the summer of 2017, the Chinese satellite group published three astounding papers that revolutionized quantum communications forever." (Dowling, 2020, p. 220)

China continues to make gains in the field. On October 2024 at a press conference held by the Mozi Quantum Technology Foundation, Pan Jianwei said he expects that by next year, China will launch two to three low-orbit satellites, which will form a constellation with the 10,000-kilometer-class high-orbit quantum satellite launched in 2027 and combine with the fiber-based quantum communication network to provide global quantum network services. He added that the number of quantum communication users in China is growing rapidly (Eastmoney Finance, 2024). China Telecom, the country's largest telecommunications company, said as of the end of last year there were 3 million end users of quantum

[9] https://petrus-euroqci.eu/ (Accessed 23 May 2025)

communication, and this year this number is expected to exceed 5 million. According to Shanghai Telecom, the first commercial quantum key distribution network at the operator level in China has been built in Shanghai, which can support no less than 1 million users. It is expected that by the end of next year, China Telecom will deploy quantum metropolitan area networks in 10-15 cities across the country, which will be gradually connected with the backbone network in the future, and with the Mozi quantum communication satellite in the sky, it will eventually form a quantum communication network integrating the earth and space infrastructures. The numbers might seem high, but on the other hand in 2021 China Telecom launched a special SIM Card that supposedly provides quantum encryption (SCMP, 2021) and that they invested an additional $434M in 2023 to create China Telecom Quantum Information Technology Group (Swayne, 2023).

In contrast, a 64 page report titled The National Quantum Initiative Supplement to the President's FY 2025 Budget (NQI, 2024) from the US does not mention the phrase QKD or quantum key distribution even once. Instead the report provides the following statement: "*Quantum Networking (QNET) includes efforts to create and use entangled quantum states that are distributed over distances and shared by multiple parties for new information technology applications and fundamental science; for example, networking of intermediate scale quantum computers (modules) for enhanced beyond-classical computing capabilities.*" (p.7). This indicates a shift away from QKD in the US context, which has been a foreseen possibility in the community but not something that was certain to happen. Both NCSS in the UK (2020) and NSA in the US (2024) had explicit positions to not endorse the use of QKD for any government or military applications for quite a while now. Similarly, the Federal Office for Information Security (BSI) in Germany also published an extensive report on potential implementation attacks to QKD systems (Marquardt et al. 2023) and does not endorse the use of current QKD systems for any government or military applications.

There are three points that can be ascertained from this limited look at the technical landscape of quantum technologies. First, there is a considerable diversity of research on how to best physically realize these technologies relying on a varying number of approaches ranging from trapping individual ions via shooting them with lasers from six directions while they float in near absolute vacuum to cooling custom made aluminium pieces to temperatures orders of magnitude colder than the outer space so that they exhibit quantum properties, and other sci-fi sounding physics feats. These of course are at different QTRLs (Purohit, et al., 2024), yet the important point here is that there is not only diversity of research, but also a diversity of research actors ranging from tech giants to small start-ups, universities to national labs, and more.

The second point is, even though the assumption in the field since almost 2016 was that the cloud model will reign supreme, in the last two years things there has been a strong uptick in the on-premise quantum computers (see Figure **C1.3.3**). This trend is particularly important because of several reasons, it shows a switch in business models by some companies, it shows that there is an appetite to buy these devices for research purposes, and the fact that it is not just the superconducting or the ion trap devices from one or two companies, but a wide range of devices from a variety of companies that are being sold, it hints at a growing potential

competition and market maturation beyond its crawling phase. Also, more on premise devices in different countries or even locations will require more technicians and distributed expertise, instead of all expertise being highly focused in only a few companies or locations.

The final point is, quantum technologies as a wider umbrella term does not have a single technical trend but contains multiple trends for its different technologies, and that sometimes results in contradicting outcomes for world regions. For example, China seems to be doubling down on its already quite extensive QKD network infrastructure, meanwhile the US is trying to leapfrog QKD networks to quantum networks with higher order capabilities, like entanglement distribution with memory storage for computational purposes, which neither the Chinese networks nor the planned EuroQCI efforts in the EU are suited for.

1.4 The Education and Outreach Landscape of Quantum Technologies

The education and outreach landscape of quantum technologies has been quickly evolving since 2016, both in terms of levels of activity and the type of activities being carried out. There are regional and national initiatives on different levels such as the National Q-12 Education Partnership[10] in the US, the Digitally Enhanced Quantum Technology Master program (DigiQ[11]) in the EU, and many global programs focusing on informal education opportunities offered freely by organizations like IBM via Qiskit Summer Schools, but also NGOs and grassroots initiatives such as QWorld, OneQuantum, QubitbyQubit, Womanium, and so on. There are also a wide range of outreach activities, especially after the launch of World Quantum Day[12] (April 14th) in 2021 to promote quantum technologies and help local enthusiast groups gain visibility.

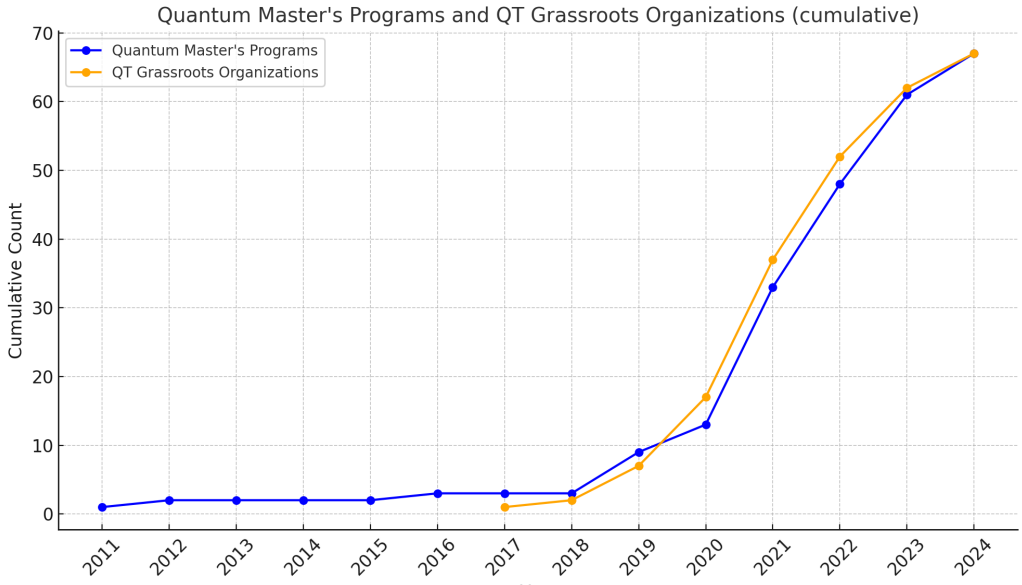


Figure **C1.4.1**: Cumulative number of Quantum Master's Programs and QT Grassroots. Constructed using data from (Goorney, et al., 2024b; Genenz, et al., 2025)

[10] https://q12education.org/ (Accessed 23 May 2025)
[11] https://www.digiq.eu/ (Accessed 23 May 2025)
[12] https://worldquantumday.org/ (Accessed 23 May 2025)

One day, while routinely checking publications for secondary data for this chapter, I realized that the numbers of QT Grassroots Organizations focused on education and outreach that we covered in our paper (Genenz, et al., 2025) are really similar to the numbers in the dataset of QT Master's Programs of a recent arxiv preprint (Goorney, et al., 2024b). Their paper investigates a growing trend of the development of masters programs in the worldwide QT education landscape, which are intended to provide graduates with the knowledge and skills to take a job in the quantum industry. Our paper was primarily on investigating the intersection of goals and values within grassroots organizations operating in the realm of QT education (Genenz, et al., 2025), but for that, we initially had to identify and count them. Comparison of these two papers resulted in Figures **C1.4.1** and **C1.4.2.**

Figure **C1.4.1** shows that the increase in the number of grassroots organizations in the field follows a very similar pattern to the increase in the number of master's programs that focus on quantum technologies. One might say that this is only expected, as formation of specialized master's programs can easily result in formation of student and volunteering organizations passionate about providing education and outreach on their primary topic of interest, quantum technologies. Yet, Figure **C1.4.2** shows that this alone cannot explain the full story, as by count, Africa has more grassroots organizations founded than in EU-27. Even if the original paper may have missed a couple specialized QT master's programs in Africa, it is highly unlikely that there are more than a few. The same argument applies to South America as well.

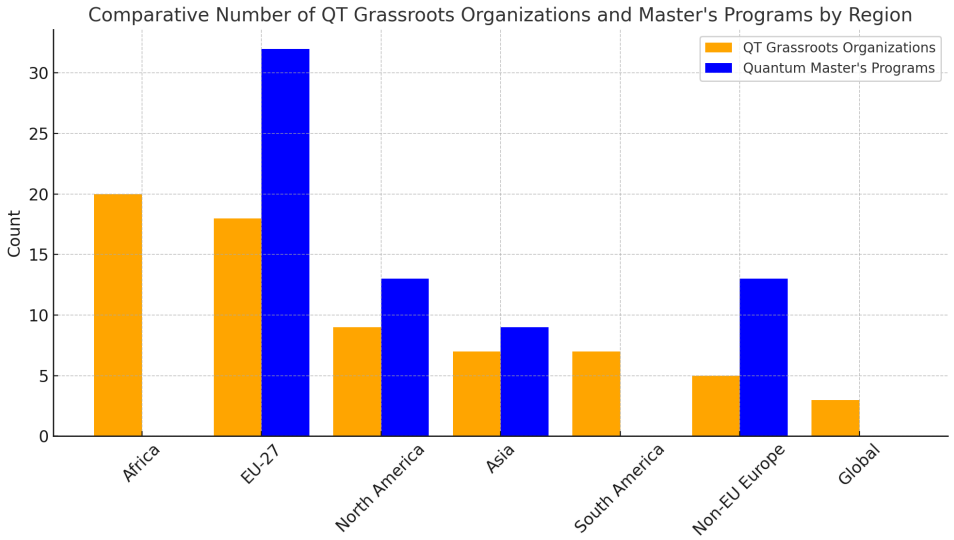


Figure **C1.4.2**: Comparison of Quantum Master's Programs and QT Grassroots Organizations focused on education and outreach by region (Goorney, et al., 2024b; Genenz, et al., 2025)

One potential explanation is lack of access to financial and structural resources in different regions, which results in the perpetuation of the digital divide into a quantum divide (Ten Holter, et al., 2022; Gercek & Seskir, 2025). Remembering Figure **C1.1.1** (QURECA, 2024), levels of sustained investment into quantum technologies are spread thin and most of the so-called Global South countries are gray colored on the map, indicating they have no centralized funding or strategy on quantum technologies announced. This can also be found when global quantum

education initiatives are investigated (Kaur & Venegas-Gomez, 2022), and even further, the same phenomena is observed within countries like the US, where the quantum technologies education programs are largely failing to reach low-income/rural students (Meyer, et al., 2024).

Quantum technologies, especially quantum computing has a history of hype (Roberson, et al., 2023), so much so that it has become a common talking point in almost all the events on quantum technologies, and there are even efforts on how to mitigate the quantum hype (Ezratty, 2022). One can even quantitatively track the (proxy) evolution of hype in the topic via tools such as Google's Ngram (Lin, et al., 2012) and Google Trends (n.d.). Performing these searches in the said tools resulted in Figures **C1.4.3** and **C1.4.4**.

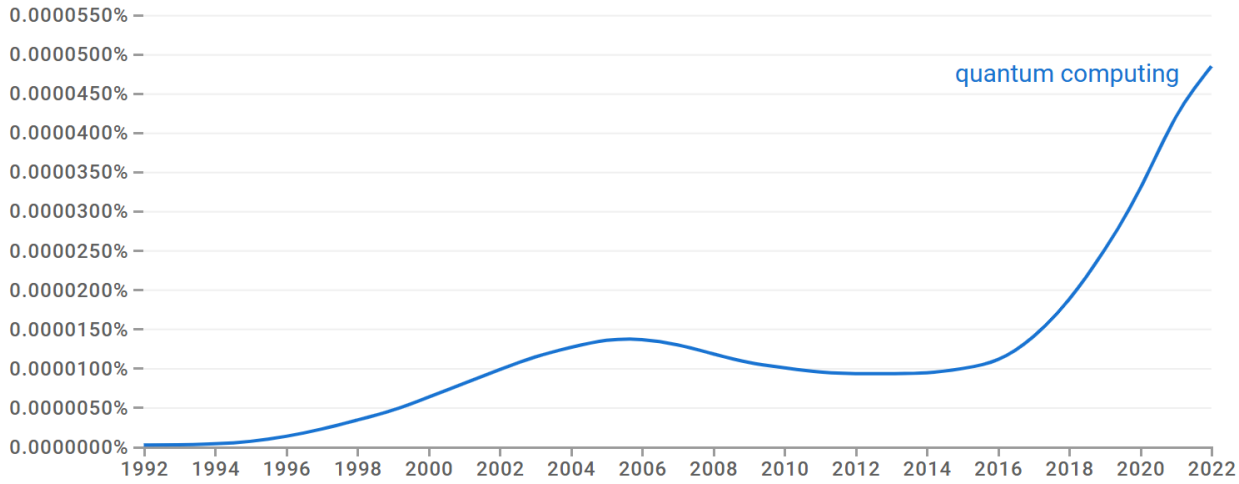


Figure **C1.4.3**: Google Ngram result for "quantum computing" covering 1992-2022

Google Ngram provides information on the frequency of the keyword being used in the books database used by Google, which covers around 8 million books from the 1500s up till 2022. Google Trends normalizes the Google search results of a topic within a period of time with respect to its highest searched day. According to Figure **C1.4.4**, there has been almost a linear amount of increase in interest to the topic of quantum computing, where two spikes, one in mid 2016 and another in late 2019 are corresponding to IBM making their quantum computer online and freely accessible in May 2016 (Vu, 2016), and the Google quantum supremacy experiment in October 2019 (Arute, 2019).

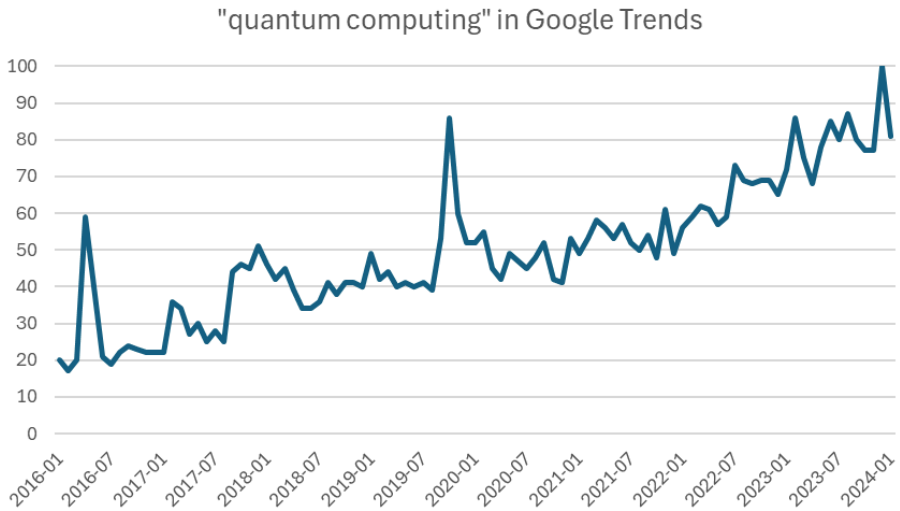


Figure **C1.4.4**: Google Trends result for “quantum computing” covering 01.2016-01.2024

One impact of hype is that it attracts students to a topic and quantum computing was no exception (Meyer, et al., 2023). It is also not surprising that the first grassroots organizations operating in the realm of QT education started appearing in 2017 on Figure **C1.4.1** (Genenz, et al., 2025), right after IBM made their quantum computer publicly accessible. Similar to me getting involved in playing around with the IBM cloud devices (as mentioned in the Prologue section), enthusiasts all around the world started using those devices via the cloud access provided by IBM. In the time period between 2016 and 2021, IBM spent around $100M to promote free access to their resources, which included tools like the Qiskit textbook, YouTube channel, hackathons, summer schools, and so on, estimated to have reached around three million people (Seskir, et al., 2023a). Meanwhile, these enthusiasts started coming together to form communities, and global non-profit organizations such as OneQuantum and QWorld were established to support the formation of these communities. Simultaneously, more established non-profit informal education providers such as The Coding School and Womanium got involved and started the programs called QubitxQubit and Womanium Quantum+AI respectively. Combined, these four organizations as a result of their training in terms of courses and workshops completed, provided certificates to more than 20.000 people from all around the globe (Seskir, et al., 2023a; Genenz, et al., 2025) and continue to operate.

Another track of development relevant for education and outreach activities in quantum technologies is the introduction of games and interactive tools for those purposes (Seskir, et al., 2022b). Development of first video games date back to the late 1950s, even predating the invention of the internet, hence it was only expected that developers of quantum computers would also get involved in creating quantum games (Wootton, 2020; Piispanen, 2023a). The first organized efforts to create quantum games go back to the early 2010s but the number of games developed started going up following 2014 (Chiofalo, et al., 2024) after the first Quantum Game Jam[13] organized as part of the Finnish Game Jam in 2014 (Figure **C1.4.5**). As of mid-2023, there were more than 350 quantum games already developed (Piispanen, 2023b).

[13] https://www.finnishgamejam.com/quantumjam2015/games/2014-games/ (Accessed 23 May 2025)

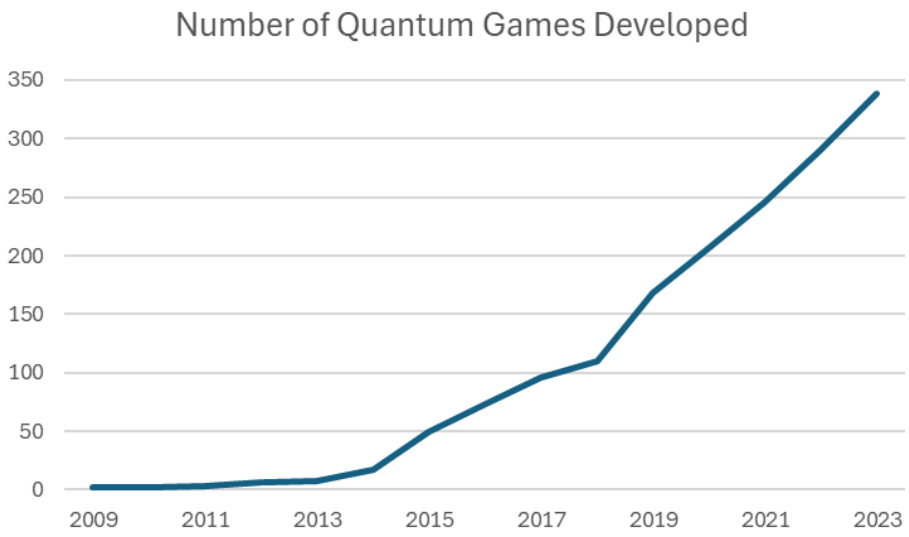


Figure **C1.4.5**: Number of Quantum Games Developed (Piispanen, 2023b; Chiofalo, et al., 2024)

In our paper titled “Quantum games and interactive tools for quantum technologies outreach and education” (Seskir, et al., 2022b) we covered eight games and interactive tools in-depth with their creators as co-authors to provide first-hand experiences from the field of quantum games and interactive tools development. Later, we followed up with another paper on the history of quantum technologies in game and software development (Skult, et al., 2024). These were all interconnected with the discussions in the literature on how to define quantum games (Piispanen, et al., 2024). One main argument provided in the quantum games for education community is that games can provide a playground for engaging forms of experimental and symbolic literacy accessible to anyone (Chiofalo, et al., 2024), and since quantum theory is highly counterintuitive, manifesting in a reality we have no direct experience of, quantum games can be useful tools to raise quantum literacy (Nita, et al., 2021). In this regard, we even organized a quantum games exhibition open to public participation in Karlsruhe as part of the Wissenschaftsreihe EFFEKTE in December 2022 titled “Ausstellung: Warum ist Quantenmechanik so wichtig beim Spielen?” (see Appendix A, Table **A1.3**).

As most of these activities were being conducted as part of and continuation of the QuTE4E pilot project under the QTEdu CSA, all these discussions on how to use games for education highlighted an important topic, was teaching quantum physics necessary and sufficient for learning quantum technologies or not. I led a survey study titled “Stakeholders, Opportunities, Problems, Solutions, and Concepts for Quantum Outreach.” The results of the survey contributed to two publications. One was on educating to the “culture” of quantum technologies (Seskir, et al., 2024b), which utilized the discipline-culture framework developed by Tseitlin and Galili (2005). This framework provided a way to distinguish between different discipline-cultures via identifying their nucleus, body, and periphery concepts (see Figure **C1.4.6**).

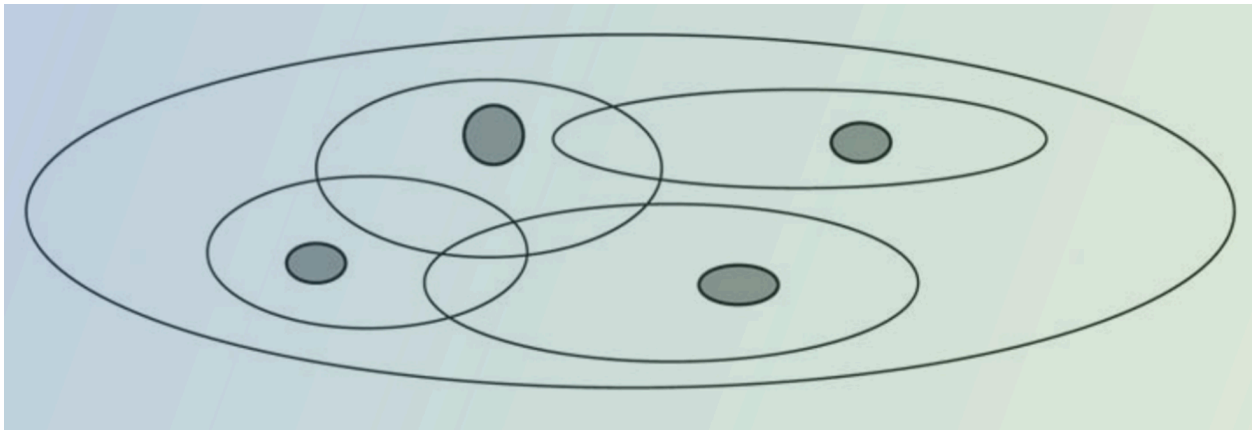


Figure **C1.4.6**: Physics as an interaction of several discipline-cultures as presented in (Seskir, et al., 2024b), adapted from (Tseitlin & Galili, 2005)

For example, the discipline-cultures of astrophysics and solid-state physics have quite different concepts, indicating the need for different curriculum and maybe even different teaching/learning approaches. Our question was whether quantum information science and technologies formed a separate enough discipline-culture to be accepted as something different than quantum physics. Our findings were indicative that this is in fact becoming the case.

This stirred some fierce discussions in the QuTE4E community, as those coming from physics education research backgrounds were mostly operating under the assumption that education on quantum technologies meant teaching quantum physics. This is not surprising, given that an overwhelming majority of academic publications on quantum technologies were being published in journals focused on quantum physics (Seskir & Aydinoglu, 2021) until the recent increase in the number of field specific journals. Yet, efforts promoting education and outreach towards non-physics oriented audiences (Salehi, et al., 2022) and the rapid increase in the number of quantum technologies specific educational programs and initiatives (see Figure **C1.4.1**) are slowly helping this tide to turn and the establishment of a new discipline-culture sometimes referred to as quantum engineering (QE) or quantum information science and engineering (QISE). I would argue that this discipline-culture is still in formation and it would be premature to say that this interdisciplinary field has already emerged as a field of its own, however, given that in the last decade the number of quantum technology specific master's programs grew from a mere couple to almost 70, this is bound to happen soon.

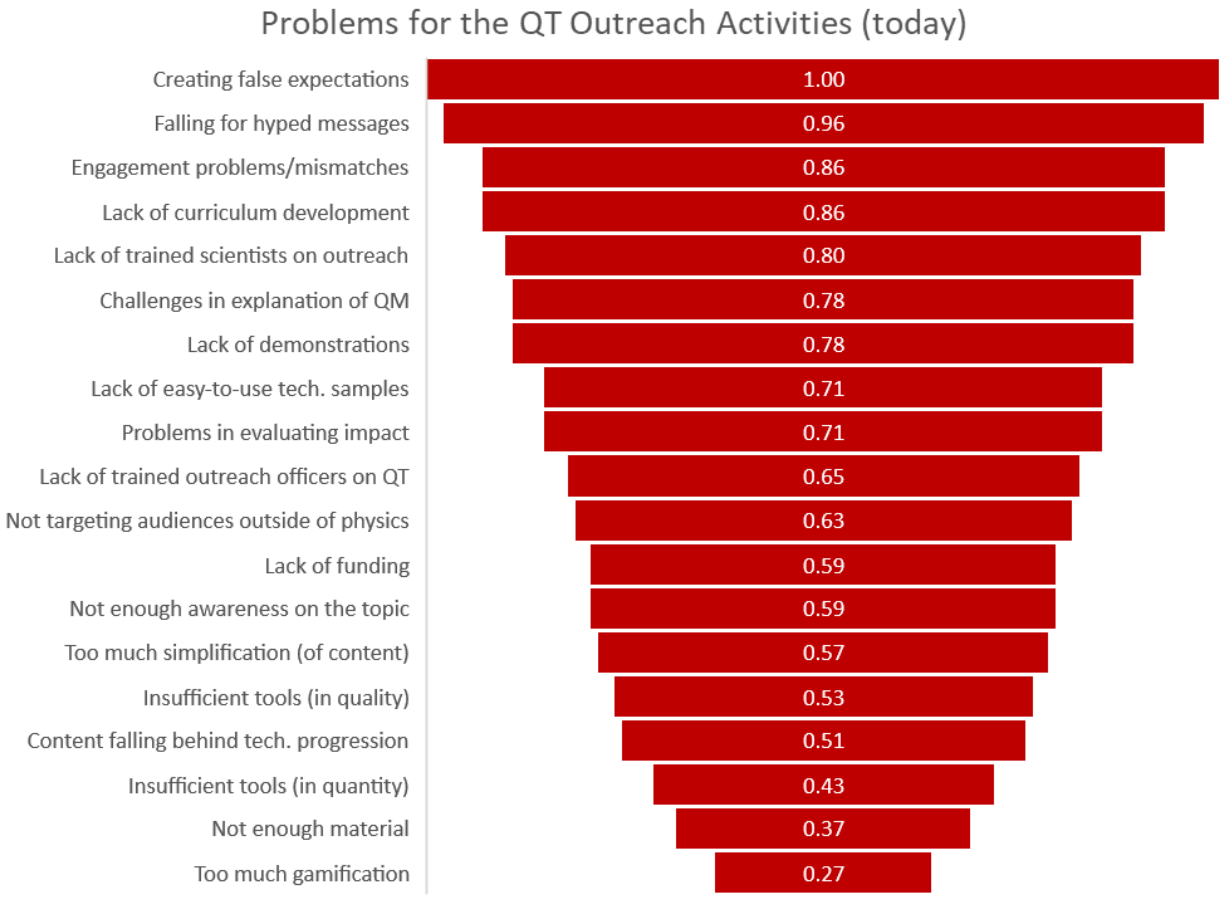


Figure **C1.4.7**: Challenges for QT outreach activities (present time), as ranked by participants of the QuTE4E Survey (Goorney, et al., 2024a)

Another publication that came as a result of the survey study was the book chapter contribution titled “Communicating Quantum Technologies in an Era of Mistrust and Misinformation” (Goorney, et al., 2024a). In the survey, we also asked the problems the outreach and education practitioners in quantum technologies encounter today (see Figure **C1.4.7**) and in 5+ years (see Figure **C1.4.8**). Since the survey ran from late 2021 to mid 2022, the ‘today’ of the study is 2022 and the 5+ years is beyond 2027. In both cases, the participants highlighted the problem of creating false expectations and hyped messaging, which is something covered in the earlier parts of this subsection as well.

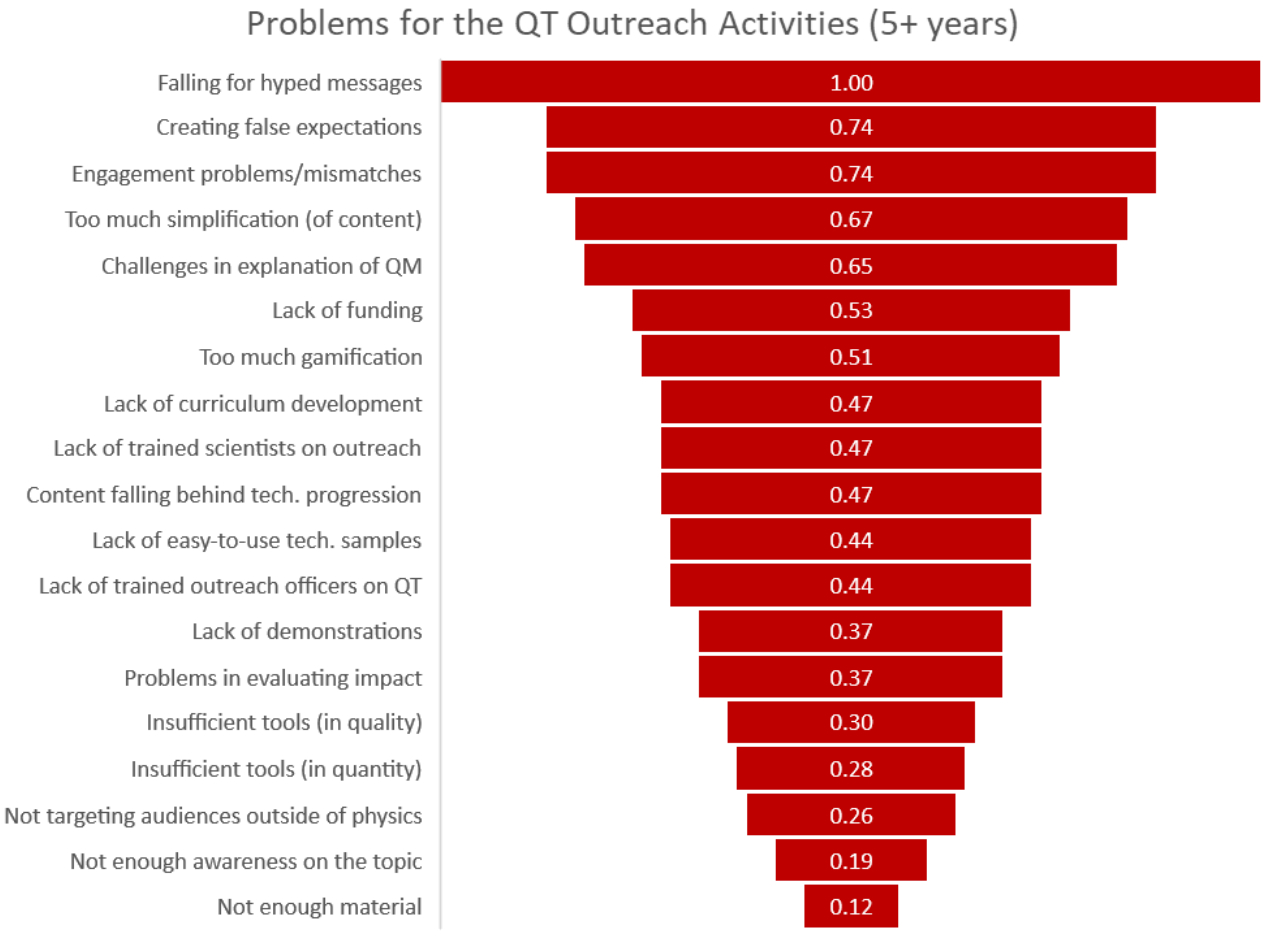


Figure **C1.4.8**: Challenges for QT outreach activities (5+ years in the future), as ranked by participants of the QuTE4E Survey (Goorney, et al., 2024a)

The last topic to be covered in this subsection on the education and outreach landscape of quantum technologies is the increasing efforts on involving arts and cultural artefacts, and their perception by the community. There are no publications related to this topic in this thesis work, but the topic has been around in circulation, especially since the increased interest in quantum games (Piispanen, 2023a). These artistic and cultural efforts range from artworks being exhibited in museums to story competitions, companies supporting artists to universities and civil society organizations supporting amateur efforts for outreach and ecosystem building purposes.

There have been some pioneering projects, such as the Quantum Shorts[14] competition that has been organized since 2012 by CQT in Singapore which collects submissions of short films and stories on quantum physics and technologies, which led to the publication of two books of edited collected volumes (Brooks, et al., 2019; Puah, 2024). Another one is the Studio Quantum

[14] https://shorts.quantumlah.org/ (Accessed 23 May 2025)

artists-in-residence[15] program by the Goethe-Institut that supported eight artists from around the globe to visit quantum technologies researchers to learn about the topic and generate artwork, which were exhibited in Berlin House of World Cultures (HKW) between 1-10 November as part of Berlin Science Week 2024.

Quantum technologies have also been increasingly visible in the cultural domain, especially as part of sci-fi genre movies and shows. I ran a summer internship project as a mentor titled "References to Quantum Technologies in Cultural Artefacts" via the QIntern program in 2022[16] to investigate how quantum technologies are covered by the mainstream cultural artefacts. There were some interesting findings. For example, an intern analyzed the city-building and economic simulation game called ANNO 2205, which was released in 2015. The game had an entire quest line for players to manufacture quantum computers using alloys from the arctic and helium-3 from the Moon to satisfy the need of investors class in the city for economic purposes. Another intern analyzed the first five seasons of the television series *The Flash* which first aired in 2014. Although there were many references to quantum physics in the first three seasons, no specific quantum technology has been mentioned. Yet, starting with season four and more in season five, there were explicit references to quantum encryption, quantum computers, and quantum sensors. In 2020, there was a one season series called *The DEVS*. It was a series focusing on a quantum computing start-up, covering espionage, philosophical debates on interpretations of quantum mechanics, existence of free will, and accumulation of power by big tech. corporations. There was also the (in)famous Ant-Man series which gave many explicit references to quantum physics, resulting in high enthusiasm (I heard on many occasions that Ant-Man was the first time some students heard about "quantum"), yet frustrated many researchers in the field due to its utter disregard for scientific accuracy.

The misappropriation of quantum mechanics has a deep history. In his book *How the hippies saved physics: Science, counterculture, and the quantum revival* (Kaiser, 2011) David Kaiser tells the story of an eccentric group of physicists in Berkeley, California in the 1970s studying quantum entanglement in terms of Eastern mysticism and psychic mind reading. They even partially received funding from the CIA to explore the possibility of using quantum mechanics for parapsychology and remote viewing purposes. Another line of confusion inserted to the public was through Deepak Chopra's *Quantum Healing* (1989), as he introduced terms like "quantum consciousness" and "quantum energy" in very speculative contexts to obfuscate the logic of his arguments. There are many other smaller examples, yet the legacy of these cases are still strong in the efforts to do outreach on quantum technologies. The social media presence of accounts and pages dedicated to quantum healing, quantum thinking etc. far outweighs the presence of proper scientific outreach media both in terms of number and in terms of followers.

[15] https://www.goethe.de/prj/lqs/en/index.html (Accessed 23 May 2025)
[16] https://qworld.net/qintern-2022/ (Accessed 23 May 2025)



Figure **C1.4.9**: Some examples of the word “quantum” used in non-scientific contexts

I always use Figure **C1.4.9** as a slide in my presentations when it makes sense, as this is a phenomenon that is almost universally frustrating for quantum physicists. It is frustrating because it would be misleading to think that this is an isolated phenomenon in the cultural domain. While doing patent analysis work for the patent landscape publication for this thesis (Seskir & Willoughby, 2023), I encountered several granted patents (mostly but not exclusively in China) that claimed to perform technical feats related to quantum healing, quantum field generation (for quantum healing), quantum energy applications (like quantum energy pendants), and so on. We even had to discuss whether to count these patents as false positives or not, as they are obviously not related to actual quantum technologies, but also very obviously exist as granted patents. Since we used an A.I. classifier for that study, we were able to train the classifier on not just what to look for, but what to exclude. After many iterations of training, it was able to (mostly) distinguish between actual quantum technology related patents and the patents such as those below, which were all covered in the datasets of earlier studies because they had to rely on keyword searches:

- “*A kind of quantum wine*” (recipe for an actual wine for “raising sleep quality”)

- “*A kind of control system of multi-functional quantum hair tonic comb*” (a comb with herbaceous plant essence for nourishing hair and massaging the head)

- “*A kind of quantum generation converting apparatus*” (a cup for drinking tea with a leak hole for honey or granulated sugar to be leaked directly into the cup).

This is an issue sometimes raised in meetings and events as well, both referring to hype and a kind of obfuscation by some commercial actors adding the word “quantum” to increase the appeal of their products (like quantum blockchain) when actually it has no real connection.

Looking at the education and outreach landscape of quantum technologies, there are three main points that are highly relevant for this thesis work. First, there is a clear upward trend in almost every aspect of education and outreach related activities. From the number of QT specific programs being founded to NGOs and grassroots communities being formed, to the number of quantum games and mentions in mainstream cultural artefacts, the topic is attracting attention. From an academic perspective this is also the case. For example, there are many academic networks being formed (such as QuBIT EDU - Quantum Didactic Community Germany[17]) to address the resulting questions from activities in this domain. There is even a dedicated conference called Quantum Science and Engineering Education Conference (QSEEC) organized yearly as part of IEEE Quantum Week[18] since 2022, it has several tracks focused solely on education and outreach topics related to quantum science and engineering.

Second point is the formation of a new discipline-culture around these technologies. This is currently an important point, as it would be premature to claim that this new discipline-culture is already formed and its boundaries are clear, yet it would also be not realistic to claim that no such thing exists and the entirety of education and outreach activities in quantum technologies can be thought of as an extension of quantum physics. From a technology assessment perspective this is also an issue about ownership by stakeholders. Quantum technologies have been a physicist playground since their inception in the 1980s. Yet, more and more 'outsiders' are getting on-board and the field has been becoming increasingly interdisciplinary. This was also highlighted by a participant to the survey (Seskir, et al., 2024b): "*Globally, this study seems to assume quantum technologies is only a problem of physics and/or physicists. A quite large part of the work involves computer scientists (algorithmics, quantum software, language) and there are already problems in communicating this towards the physics community. This difficulty of communication goes both ways.*"

As stated by the participant's quote above, the difficulty of communication goes both ways. Most physicists involved in the field expect to have clear ownership, as they tend to think quantum technologies are an extension of quantum physics. Yet, this is not an inclusive or welcoming attitude, and furthermore quantum technologies are not a mere extension of quantum physics, they require active participation and onboarding of computer scientists, mathematicians, several types of engineers, and so on. This has been a topic of contestation for a while, even leading to questions such as "why do we expect everything to be done by quantum physics PhDs?" at one of the EQTCs.

The final point is about the importance of hype, expectations, and perception both by the public and within the professional communities. This is a highly relevant point, as the field has been riding a hype wave, yet there is a general consensus about hype having risks for the field altogether (such as a 'quantum winter'). For example, the I-ARPA director plainly said at the Quantum World Congress in 2024 that hype is bad and might lead to discontinuation of funding, warning the community. Attitudes similar to this are common in the community and it also fuels a general wariness and distance towards cultural representation of quantum technologies.

[17] https://qubit-edu.de/en/index.php (Accessed 23 May 2025)
[18] https://qce.quantum.ieee.org/ (Accessed 23 May 2025)

1.5 The Geopolitical Landscape of Quantum Technologies

Quantum technologies, ever since its inception in early 1980s had relevance for geopolitically relevant applications. The first major technological breakthrough in quantum technologies was the QKD protocol, introduced by Charles Bennett and Gilles Brassard in 1983 and published in 1984 as BB84 (Bennett & Brassard, 1984), promising unconditionally secure communications via using natural laws instead of mathematical tricks. The Quantum Information Science and Technology (QuIST) program was established in 2001 by DARPA[19] and by 2004 they had established the first QKD network for a data-encryption framework for protecting a fiber-optic loop.

Another landmark development was Peter Shor's algorithm, published in 1994 (Shor, 1994), which demonstrated an exponential speed-up for prime factorization. This algorithm poses a significant threat to public key cryptography, the backbone of secure internet communication, with the potential to render it obsolete. The Snowden revelations revealed that the NSA invested $80 million in a project called "Penetrating Hard Targets" to develop a cryptographically relevant quantum computer (Rich & Gellman, 2014). And further evidence suggests that as early as 2006, the NSA was collaborating with universities on quantum computer development (IOPP, 2014). Since Xi Jinping assumed the presidency, China has significantly intensified its focus on quantum communication, driven by economic goals and concerns over national security, particularly in response to Snowden's 2013 revelations about the US surveillance. Viewing quantum communication as critical to safeguarding its information and cyberspace independence, Chinese leadership has prioritized indigenous innovation in quantum technologies, setting long-term goals for global competitiveness and strategic advancement by 2030 (Sharma, 2018).

A third major application, quantum sensors, has shown promise in areas such as detecting stealth objects using quantum radars (Durak et al., 2022), identifying submarines with quantum gravimeters (Qiu et al., 2016), or using advanced quantum clocks and other navigational systems to have fully GPS-independent PNT applications that, as an example, can allow uninterrupted submarine operations (Kubiak, 2020).

The remnants of interest from defence and security sectors towards quantum technologies can also be seen in the previous sections of this chapter. For example, Figure **C1.2.3** shows that DoD in the US is in the top four of funding agencies of research in quantum technologies globally, and according to the data from Figure **C1.2.4** around 20-25% of all published articles on quantum technologies coming out of the US has at least partial funding received from the DoD. Similarly, following the developments highlighted in Figure **C1.3.3**, it is known that organizations related to the US military, such as the Air Force Research Laboratory procured quantum computers with different modalities from several different companies to do active research on them. An extensive and detailed review study by Michal Krelina highlights (**Figure C1.5.1**) a long list of potential quantum technology uses for military applications (Krelina, 2021).

[19] https://www.darpa.mil/about/innovation-timeline (Accessed 23 May 2025)

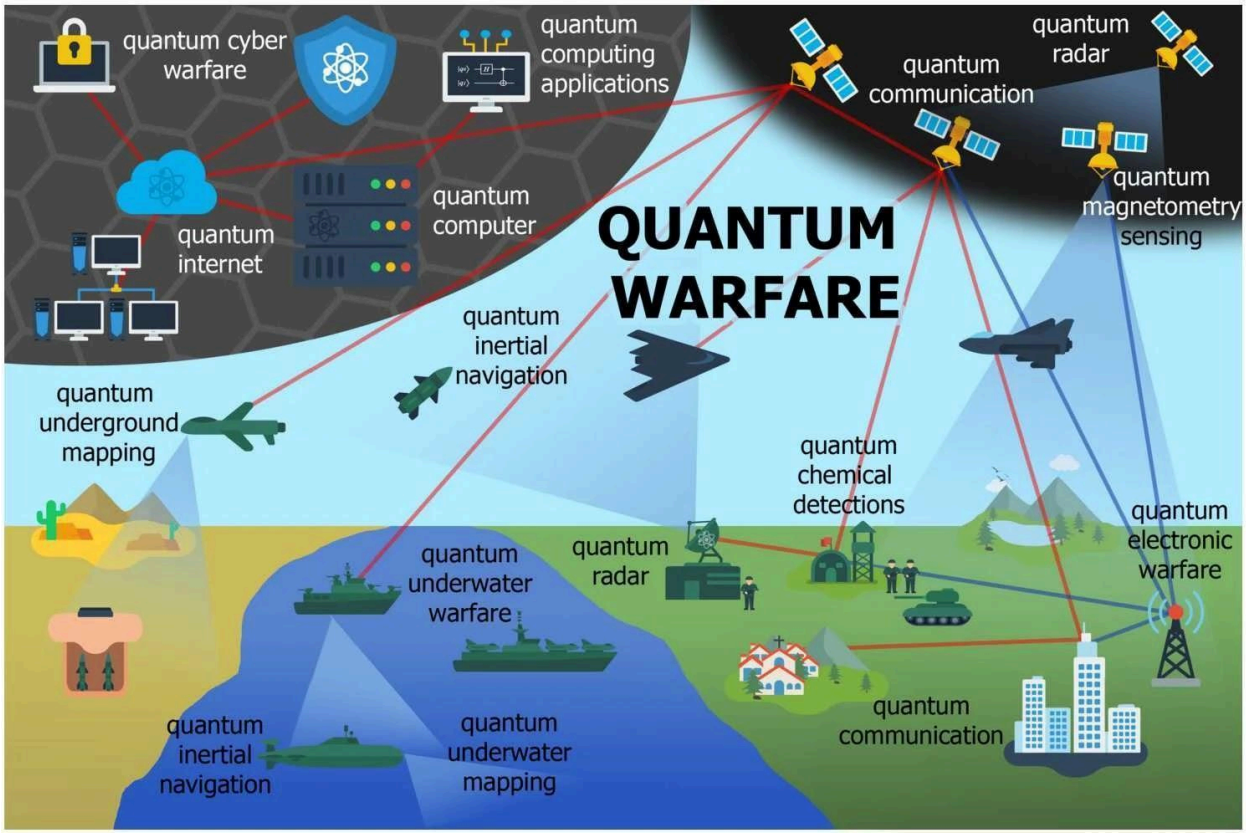


Figure **C1.5.1**: A sketch of quantum warfare utilizing various QT systems (Krelina, 2021)

The increasing importance of quantum technologies for geopolitical and military relevant activities are sometimes referred to as a quantum arms race in the media (Giles, 2019). A good example of how this 'race' progresses is given by Dowling in his book (2020, p. 222-223):

"*Just like Sputnik led to the founding of NASA, Mozi led to the founding of the new U.S. National Quantum Initiative Act. In June of 2017, right when the data from Mozi was made public, it became immediately clear the satellite was not a hoax. The Science Committee of the U.S. House of Representatives approached the U.S. National Photonics Initiative (NPI) and asked for a white paper outlining a U.S. response to the Chinese breakthrough. The NPI responded with an 11-page document titled "Call For A National Quantum Initiative: Proposal to address the urgent need to develop the information infrastructure of tomorrow." This document served as a primer for the National Quantum Initiative Act, signed off by the President in December of 2018. That is amazingly quick for the U.S. government. In only 18 months, they went from "the Chinese quantum satellite is a hoax" to the National Quantum Initiative Act.*"

There were calls to keep research on quantum technologies global and open, even between Russia and the US (Biamonte, et al., 2019), yet as expected, this mutually competitive aspect only accelerated since the Russian invasion of Ukraine. That, eventually, even culminated in the formal development of a Quantum Strategy by NATO (2024). To keep track of the developments in this field and make first hand observations, I attended three events in 2023 and 2024.

The first one was a Symposium on Quantum Technology for Defence and Security[20] organized by NATO STO, which was a two-day event organized in Amsterdam, October 2023. The event had around three hundred participants, ranging from generals to researchers, defence ministry personnel to diplomatic attaches of allied nations (like Japan). The event had many interesting details. For example, in the pre-event dinner the previous day during the get together, as entertainment we were invited to play a game of quantum tic-tac-toe developed by a Colonel in the Dutch army. There were 10 panels to play the game on and people started playing it immediately, all panels were full in the beginning. The particularly interesting point for me was that they had a SpinQ device to run the quantum part of the game, given to them by TNO. SpinQ is a Chinese company selling two-qubit NMR desktop quantum computers for educational purposes. When I asked the person in charge of operating the games on the device why they were using a Chinese quantum computer at a NATO event, he said it is what they have and there were no other similar devices available, and that they want to get familiar with the technology to learn how it works.

The first day of the symposium was also quite interesting. For example, during the opening presentations there was a very strong focus on quantum sensing and a bit on quantum communications but almost nothing on quantum computing. Someone in the audience asked why not focus on quantum computing as it is the one with the most promise. The speaker answered by saying "*We see that sensing can help us, we don't see yet that quantum computing can help us, it is not like AI... I'm sorry, we are not there yet*." There was also the slogan of "Mastering the very small to win future conflicts" used.

China was a topic mentioned many many times. Some speakers talked about a Chinese "IP Lawfare" approach on patenting. There were also some slight complaints by speakers about how in the West scientists are reluctant to work on military efforts, but in China they enjoy the authoritarian civil-military fusion. There were also explicit mentions of China as the world leader in quantum communications, having extensive capabilities in QKD, and even beyond quantum communications in areas such as sensing, underwater, and radar.

Sir Peter Knight gave a plenary session, where he mentioned GPS and GNSS as enablers of the modern economy, as a free critical infrastructure. This was particularly relevant as mentioned previously, GPS-free operation capabilities are expected to benefit quite a bit from the development of novel quantum technologies (Kubiak, 2020). He also mentioned several interesting points like saying "*I really love gravity, you can't shield against gravity*" to highlight the potential use cases of quantum and quantum-inspired gravimeters. Finally, he openly said "*The problem we have in the field is extreme hype in the press*." As highlighted on Figures **C1.4.3** and **C1.4.4** this can be seen in quantitative terms as well, and via Figures **C1.4.7** and **C1.4.8** we know that hype and creating false expectations are seen as the primary challenge of quantum outreach activities by the practitioner communities.

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20 https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/Forms/Meeting%20Proceedings%20Document%20Set/docsethomepage.aspx?ID=46238 (Accessed 23 May 2025)

The second event was the Responsible Innovation Defence and Security Conference in Brussels in November 2023. This was an event directed to a more general audience and the difference between the NATO STO event and this one in terms of how quantum technologies is covered was quite clear. During the entire two days quantum technologies was only mentioned a handful of times, and almost always mentioned as one of the emerging and disruptive technologies (EDTs) like A.I., biotechnology, and space. Yet, this was quite an educational event in terms of how the defence and security stakeholders perceive themselves and the environment they operate in. For example, a moderator from the defence innovation fund opened up a session saying that in Europe "...*when I went to innovation ecosystem conferences and wore a NATO pin, I would have worn a MAGA hat, the reaction was the same... the EU taxonomy put us on par with the tobacco companies and such in terms of investability... Ukraine was a wake up call, to defend yourself you need a defence industry.*"

In both events, there was a strong focus on being fast. At the Brussels event, one of the speakers described it as "*History is accelerating like crazy, we need to innovate differently*." At the Amsterdam event, one of the key speakers emphasized "*Our opponents will move fast, so innovation is key in keeping competitive*." Another common thread was the focus on setting standards. As one of the main speakers in the Amsterdam event plainly said NATO should "*Set standards and favor interoperability*" and in the Brussels event another speaker said "*NATO has the power of standardization, which is pure gold*."

Both events also had a similar tone in terms of how responsibility and societal relevance comes into play. In the opening talk of the Amsterdam event, the speaker said "*quantum should help the military efforts*", and our safety depends on a "*whole of a society approach*". Yet, there were also explicit mentions such as talking about the importance of addressing the emerging quantum divide. Also, both Pieter Vermaas, who leads ethics research for the Dutch Quantum Delta NL programme for the development of quantum technologies, and I gave talks at the Amsterdam event (Seskir, et al., 2024a) which were focusing on responsible quantum technologies. In the Brussels event the focus was more clear, given that the event was dedicated to responsible innovation. One of the opening speeches highlighted that sentiment by stating "*We need to innovate responsibly, our young citizens and societies want and expect from us to keep a technological edge but do it responsibly. NATO emerged from the ruins of 2. World War, so we need to be careful about these. There needs to be a balance between regulation and competition, stifling innovation can mean losing technological edge, but letting them develop without guardrails is also very dangerous*." Another speaker said to be able to get support from society "*you need to show that the technology will be used in a morally acceptable manner, consistent with their values.*"

More focus was put on the topic of trust and transparency. A high ranking Dutch official said for NATO related efforts the average procurement period is 16.2 years, and that there are no transparent processes for them to tell their problems to innovators. He also added "*We have an image problem, war in Ukraine helped a little bit, but there is a trust problem*". Another high ranking military official from Europe said "*We have secrets against the adversaries, we don't have secrets from the governments, we should be entirely transparent to the governments*."

There were also some other quotes and mentions that were highly indicative that quantum is still being perceived as a mystery topic by many. For example, a Colonel who was in charge of presenting the biotechnology and human enhancement plans of NATO said "*...living sensors, biocomputing, there is something called quantum biology which confuses me because quantum by self is also difficult to understand…*", a high ranking official when giving the opening speech of Amsterdam event said "*Einstein didn't get it, so who am I to get it…*", a program officer from NATO said the quantum scientists in the room are geniuses and apologized for being just an engineer.

Some focus was put on the convergence of different technologies, especially in the Brussels event, but also convergence of topics related to emerging technologies. The NATO Deputy Secretary General at the Brussels event mentioned the convergence of geopolitics, geoeconomics, and developing technologies, and that the illusion of the end of history is over. He also said "*Think about generative AI and quantum computing merging in the coming years. These are the most exciting and dangerous times in NATO history*." Someone from the UK defense ministry asked "*In AI everyone has principles, that is great... There are principles in quantum, human augmentation, cyber... Is there a convergence? Should we have a list of principles common to all, to prevent a miasma of overlapping and conflicting values?*"

One thing I noticed during both of the events was the utter lack of mention of the UN SDGs. The Environmental, Social, and Governance (ESG) considerations for investment options were mentioned and discussed extensively in the Brussels event, there was even an argument from a speaker on the line of investing in defence is ESG, without security ESG doesn't matter, Ukraine showed this. Yet, even at the Responsible Innovation Meets Climate Action: Advancing Sustainability in Defence session, there were barely any mentions of SDGs.

The third event I attended was the European Conference Quantum Technologies for Defence Current and Future Capabilities organized by the European Network Of Defence-Related Regions (ENDR), with the participation of the Ukrainian Cluster Alliance and a delegation of defence researchers from Ukraine. This was also a particularly informative event to understand the relation of quantum technologies topics to the ongoing developments in defence, especially Ukraine. For example, on the topic of Ukraine and the EU relations in terms of technology development the moderator said "*You are more motivated than us*." and the Ukrainian researcher replied "*Yes, we want to live*." There was also someone from the Ukrainian delegation who had strong opinions about ethics as a primarily limiting thing, he simply said "*in war-times, ethics gets you killed*." Yet he also emphasized that they value it because they are European.

There were also practical concerns. As an example, a researcher from Poland said it took them three years to find a good ion-trapper for their group. He emphasized that talent is the main bottleneck, you can find a lot of people who can do the basic research, but it is a nightmare to find someone with necessary industry skills. He said "*For example, when you are talking about 10 Gbit rate QKD it is a completely different level than a tabletop implementation of QKD*."

During the workshop this was discussed extensively and it was said that the top reason for the slowness of developing quantum technology, even if enough funding was available, is the lack of qualified people. There was a brief discussion on whether industrial retraining can solve this, yet the seeming consensus in the room was that siphoning a highly qualified workforce from other emerging or relevant technologies wouldn't be an optimal solution and there is a need to train more qualified people with necessary industry skills. Another topic discussed was integration of Ukraine into programs such as QuantERA, however the relevant party from the commission informed the room that for participation in QuantERA the country would have to put funds into it, he said for example UK re-joined QuantERA recently. It was said that Ukraine can't pay for such international research programs because war expenses have the highest priorities.

One common theme that was mentioned in all events was that currently Ukraine is a testing ground for defence technologies. This was highlighted by Ukrainian parties as a selling point for defence companies to test their products in the Ukrainian battlefields, and things that work can quickly be pushed through the bureaucracy and get deployed. The general tone and theme was that none of the quantum technologies are at those levels, hence the war in Ukraine would probably not see quantum technologies used in it.

These three events allowed me to gain some insight into the developing yet complex relationship between quantum technologies and defence and security domains. For example, my talk at the Amsterdam event covered some previous cases for the narratives covered in the publication (Seskir, et al., 2024a), one such case was the Y2K-readiness spending leading to an estimated $300-$500 billion globally. I drew parallels to the Q-Day narrative, where the development of a quantum computer capable of running Shor's algorithm (1994) rendered current cryptographic infrastructure mostly obsolete. After my talk during a coffee break, someone came and congratulated me for the talk, but he also said I have no idea how hard it was to convince the authorities to take that issue seriously, and even if there was overspending it helped avert a lot of serious problems. This was a good counter-argument for me, retrospectively one can estimate that there was overspending (Doward, 2000), yet this knowledge is hardly ever readily available when the threat is still present and it is difficult for those who are tasked with mitigating the threat to also keep the opportunity cost questions in mind. If a government spends $100 billion instead of $50 billion towards an issue, there is an opportunity cost of $50 billion. One might have invested that $50 billion towards addressing other issues. Yet, if the government spends not enough to address the issue, then there will also be the harm caused by the issue which introduces a considerable uncertainty when making these calculations. Retrospectively, there is little uncertainty, we can estimate from other sources, such as Russia in the Y2K case (Doward, 2000), how much harm the Y2K glitch would have cost to our systems. The same applies to the potential threat caused by quantum computers, the so to speak Q-Day narrative. From a security perspective, there is considerable uncertainty involved in having that vulnerability and trying to come up with the exact proportional response in terms of € or $ amounts to spend can really only be calculated after the threat is realized.

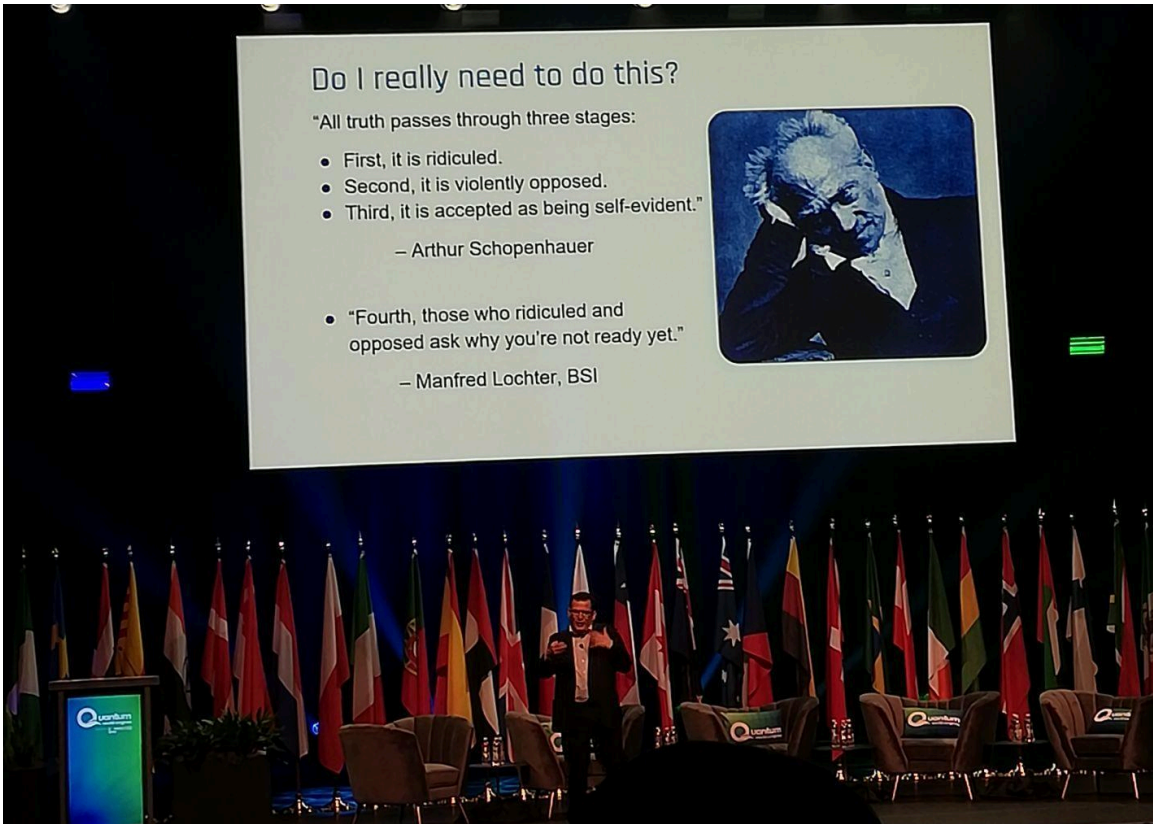


Figure **C1.5.2**: A photo I took from Michele Mosca's presentation at the QWC 2024

To get this narrative and topic of discussion one doesn't necessarily have to go to NATO or ENDR events. At the Quantum World Congress, annually organized at Washington D.C., this is also a topic raised. Figure **C1.5.2** is a photo I took from Michele Mosca's presentation, who is the main author for the Quantum Threat Timeline reports[21] published yearly by the Global Risk Institute that keeps track of expert opinion and technical developments on the timeline for a cryptographically relevant quantum computer. He came up with a basic approach sometimes referred to as Mosca's theorem, where if one have:

- X = security shelf life,
- Y= migration time,
- Z= collapse time,
- if X + Y > Z, then worry.

Meaning that if one is operating with a security infrastructure that has X years of shelf life, and it takes Y years to migrate to a quantum-secure infrastructure, and there is high probability that in Z years there will be a quantum computer capable of rendering your current capabilities invalid, then there is a reason to worry. I took the photo and wanted to put it in the thesis as it also gives homage to Manfred Lochter, who is leading the efforts against the quantum threat at BSI and who has a somewhat famously anti-QKD stance (Lochter, 2022).

[21] https://globalriskinstitute.org/publication/the-race-is-on-quantum-threat-timeline-2022-primer/ (Accessed 23 May 2025)

This topic of the use of QKD in terms of geopolitically relevant applications is a point of contention between different stakeholders. Post-quantum cryptography (PQC) is perceived as the more realistic and applicable solution to the quantum threat, which doesn't rely on any new or fancy hardware and only requires upgrading the cryptographic protocols and software. It is not easy by any means, it requires a layered overhaul of the entire cybersecurity infrastructure which will take time and considerable resources. Yet, it is a much cheaper alternative compared to having dedicated QKD hardware manufactured and installed en masse. Some QKD proponents argue that "*post-quantum-cryptography… is a new- fangled public-key system that they hope – but cannot prove! – is immune to an attack by a quantum computer*" (Dowling, 2020, p.186). This line of argument has some merit, for example the SIKE cryptographic algorithm, a fourth and final-round candidate of the NIST PQC standards competition, was broken by a team (Castryck & Decru, 2023) not using a quantum computer, but a single core old laptop in 62 minutes. Similarly, a third-round candidate FALCON Post-Quantum Signature Scheme was previously shown to be faulty (Karabulut & Aysu, 2021).

These developments support the argument of QKD proponents, where with PQC it is not possible to prove that any adopted algorithm is foolproof. In comparison the PQC proponents argue that QKD, although unconditionally secure in theory, is definitely not so in practice. BSI published an extensive report on potential implementation attacks to QKD systems (Marquardt et al. 2023), and both NCSS in the UK (2020) and NSA in the US (2024) had explicit positions of not endorsing QKD. The 2025 budget for NQI in the US does not reference the use of QKD even once. Meanwhile, Pan Jianwei in China expects a constellation of several low orbit and a 10,000-kilometer-class high-orbit quantum satellites to be launched by 2027 and combined with the fiber-based quantum communication network to provide global quantum network services (Eastmoney Finance, 2024).

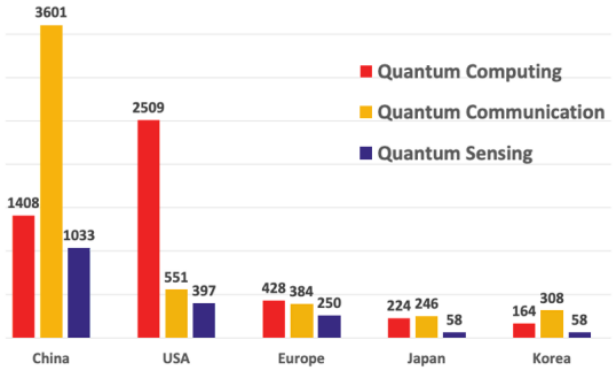


Figure **C1.5.3**: Number of patent families per quantum technology by region (QuIC, 2024)

In Europe, EuroQCI efforts are focusing on QKD (see Figure **C1.3.4**) but these efforts are relatively late and behind other regions in terms of generating intellectual property, especially compared to China (QuIC, 2024; see Figure **C1.5.3**). Apparently there were previous attempts in Europe to promote these technologies, but they were not supported. In China, they found willing ears.

"*It is of interest to note that Pan's mentor (and occasional competitor) Anton Zeilinger had a similar scheme to test quantum theory from space that he had proposed a decade ago to the European Space Agency. The project was not funded. The genius of the Chinese program was to sell their satellite to their government primarily as a state security tool and then add a couple of hitchhiking payloads to test the quantum theory*." (Dowling, 2020, p. 221)

Given all these, it seems that the global response to the potential quantum threat may be fractured. In the US, National Security Memorandum 10 (NSM-10) establishes the year 2035 as the primary target for completing the migration to PQC across Federal systems (Moody, et al., 2024, p.11). In Europe, although there are recommendations on a coordinated implementation roadmap for the transition to PQC[22], the progress has been slow. This led to declaration by the BSI and partners from 17 other EU member states demanding transition to PQC as soon as possible, latest by the end of 2030[23]. The BSI President Claudia Plattner stated the need for this transition by saying "*Powerful quantum computers could offer huge potential in the future. At the same time, however, they also threaten the security of our entire digital infrastructure. That's why we need to act now and take protective measures*."

Standards play an important role in these discussions. A thesis work titled "The impact of quantum technologies on NATO's security and defence posture" (Danilas, 2024) highlights in their findings the need for security standards of quantum technologies to be developed in parallel with the development of new technologies (p. 77). The same work also highlights that some practical use cases of the applications of quantum technologies are limited in the military context, such as QKD (p. 76). Yet it is not just QKD or PQC that needs standards. The future of quantum networking has applications beyond just communication security, such as distributed blind quantum computation (Wei, et al., 2024). A list of use cases for the quantum internet ranging from distributed sensing to clock synchronisation is provided on the website of the Quantum Internet Alliance[24], a community of multidisciplinary institutions and industry across Europe working on creating an ecosystem for quantum internet development. There is also the Quantum Internet Research Group (QIRG) led by Rodney Van Meter and Wojciech Kozlowski, formed under the Internet Engineering Task Force (IETF), a standards organization for the Internet, responsible for the technical standards that make up the Internet protocol suite.

The standards issue also ties to the supply chains discussions. As described in the section on The Technical Landscape of Quantum Technologies, there are several different ways to physically realize a quantum system. These range from trapping ions with lasers in near absolute vacuum conditions, that require high-quality lasers, efficient vacuum pumps, effective sealing chambers, etc. In comparison, a superconducting quantum circuit approach requires custom made cryogenic systems, closed cycle helium-3 circulation systems, high precision

[22] https://digital-strategy.ec.europa.eu/en/library/recommendation-coordinated-implementation-roadmap-transition-post-quantum-cryptography (Accessed 23 May 2025)

[23] https://www.bsi.bund.de/EN/Service-Navi/Presse/Pressemitteilungen/Presse2024/241127_Post-Quantum_Cryptography.html (Accessed 23 May 2025)

[24] https://quantuminternetalliance.org/quantum-internet-use-cases/ (Accessed 23 May 2025)

nanofabrication infrastructure and lithography equipment, top quality aluminium processing, and so on. Photonics quantum systems require really good single-photon sources and detectors. Silicon, NV, and others have quite different requirements as well. Depending on which modality will become the dominant one, the supply chains that need to be established will involve different competences, companies, and countries.

To address these, there are preemptive actions taken by several different actors. One of the leading efforts in this domain in Europe is from the QDNL in the Netherlands. They published a series of reports on mapping quantum supply chains, with the overall title series '*Towards European technology sovereignty in an emerging industry*.' These reports cover supply chains for quantum computers (Mans, et al., 2023a), quantum communication (Mans, et al., 2023b), quantum sensing (Osorio Tamayo, et al., 2024), and critical raw materials (Mans, et al., 2023c). The reports follow the terminology used from the CEN-CENELEC FGQT standardization roadmap (CEN-CENELEC, 2023), and a methodology of mapping EU-substitutability vs. market concentration with a 2x2 matrix approach in the end. An example is given in **Figure C1.5.4**.

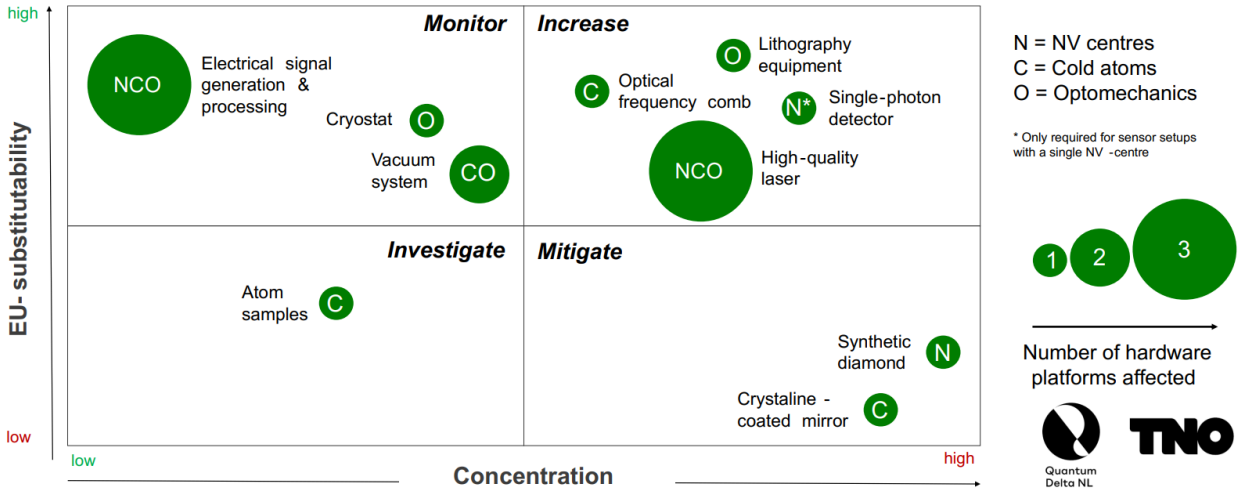


Figure **C1.5.4**: Result of the critical component mapping for quantum sensing in the Dutch ecosystem (Osorio Tamayo, et al., 2024)

Of course our Dutch colleagues are not the only ones involved in this analysis. There are others, such as the Stanford Center for Responsible Quantum Technology that aim at understanding critical raw materials supply chains in quantum technologies (Lee, 2023), and others are expected to join these discussions as the field matures.

The discussions on geopolitics of quantum technologies are not limited to military and defence, or the standardization and supply chains topics. There has also been quite a bit of literature and debate on how to approach the development and use of these technologies in the Global South. A report commissioned by the Research Group on the Law and Governance of Quantum Technologies at the University of Amsterdam titled "Quantum Computing and the G-77" (AWO, 2024) tries to tackle this question by looking at the G-77 countries, which excludes East Asian economies including Japan, South Korea, and Taiwan; emerging markets such as Turkey; and

those within Eastern Europe (AWO, 2024, p.4). In the report, they develop a typology for the G-77 states with three options: Build, Procure, or Cloud Access (AWO, 2024, p.7). In the report, China, India, and Singapore are covered under Build category, while only UAE is covered under Procure and all the rest are put under Cloud Access. China, India, and Singapore are members of G77, but they are hardly accepted as Global South countries. Also, countries like UAE, Qatar, and Saudi Arabia are not poor states, which is usually associated with being a part of the Global South group. UAE and Qatar have almost double income per capita compared to some EU member states such as Romania and Bulgaria. Hence, neither the blanket statements about the Global South or equating G-77 with the imagined Global South actually works. Yet, it is an open and important question that how geopolitical developments between NATO and its adversaries (primarily Russia and China) will impact other states.

In this regard, with the Rajaratnam School of International Studies (RSIS) in Singapore, we organized an event titled "Responsible Quantum Technologies: Impact of Geopolitics in the Indo-Pacific Region"[25]. RSIS already had previous expertise on the topic[26] and the event was jointly organized by ITAS, RSIS, CQT (the main research center on quantum technologies in Singapore), and SGInnovate (is the government-owned innovation platform in Singapore centred on the development of deep technology). In addition to Singapore, we hosted members from the quantum technologies ecosystems of Thailand, Malaysia, Philippines, Australia, India, also participants from organizations like the United Nations Institute for Disarmament Research (UNIDIR) and the private sector (such as large and small companies, and venture capital). The event was quite informative on many fronts. For example, I learned that there is a very strict export control regime in China regarding their QKD devices. Similarly, we discussed extensively on the potential impact of evolving export control regimes coming out of the US and being adopted by many allied states (such as Australia, the UK, Germany, Spain, and so on). It was quite interesting to hear from the venture capital participants that introduction of strict export controls signals that this is a very serious technology, and that even though it reduces the amount of short-term investment, it definitely puts the technology on the radar of many investment actors. Their logic was if it wasn't serious, they wouldn't have put export controls on it. It also pushes smaller states to invest in local or regional capabilities. As an example, Turkey, a NATO country that experienced export bans by other NATO countries often, increased its investments into quantum technologies rapidly in the recent years which culminated into the launch of their first quantum computer in November 2024[27], putting it under the Build category.

The geopolitical landscape of quantum technologies is a rapidly evolving one, especially due to the rapidly evolving geopolitical landscape in general. A recent report titled "Advancing international cooperation in quantum information science and technology" (NSTC, 2024) from

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[25] https://www.rsis.edu.sg/event/responsible-quantum-technologies-impact-of-geopolitics-in-the-indo-pacific-region/ (Accessed 23 May 2025)

[26] https://www.rsis.edu.sg/event/rsis-virtual-roundtable-quantum-sensing-and-future-warfare/ (Accessed 23 May 2025)

[27] https://quantumcomputingreport.com/turkey-launches-first-5-qubit-quantum-computer-called-quant-marking-national-technology-breakthrough-for-the-country/ (Accessed 23 May 2025)

the US National Science and Technology Council (NSTC) mentions China only once, and that is under the challenges section for their recommendations (p.8). Yet we know from Figure **C1.2.5** that even though it decreased from its peak of 15%, still more than 10% of research in quantum technologies coming out of the US have some collaboration with and dependency on China. This fragmentation of research in quantum technologies can only be expected to increase as the geopolitical tensions increase between regions, the days of an American researcher in Russia calling for keeping quantum computing research global and open (Biamonte, et al., 2019) are not likely to be returned in the near term.

The risk of closing the borders too much and focusing inward is also being raised within the community. Some argue that technological protectionism has the risk of causing moral isolationism (Shelley-Egan & Vermaas, 2024), while others highlight the potential for exacerbating the current inequalities (Ten Holter, et al., 2022). Yet the attitudes towards more openness are pushed back by security proponents when news like Iranian quantum computer development for maritime security (Wickens, 2023) starts circulating in the media, with an Iranian Rear Admiral proudly introducing a FPGA board as a quantum processor by mistake. These proponents argue that keeping a strategic edge comes from the asymmetry of knowledge and capabilities between countries and an 'open' ecosystem would primarily benefit their relatively laggard adversaries (such as Iran and North Korea).

There are four points that need to be highlighted from this section. First is the debate on open-close border collaborations due to geopolitical conditions. This is likely to become more important as with the beginning of the second Trump presidency is expected to lead into a more protectionist trade and security regime in the US, which will have ripple effects and limit the global 'free trade' ideology that reigned supreme since the dissolution of the Soviet Union. Second point is whether quantum technologies have any actual near term relevance for military conflicts, which the answer is not clear but seems to be no. One of the main debates at the ENDR event was whether it makes sense for Ukrainians to invest in high-end quantum sensors or just buy hundreds of thousands of cheap drones, put in simple autonomous targeting systems and send them free in the battlelines. There was very little debate on whether the use of autonomous weapon systems would be legal or ethical or not either, just that whether it would yield superior results or not. If the promises of quantum technologies can be delivered via other technologies, such as A.I. and drones, then it is likely that the defence appetite for quantum technologies might reduce. This would have considerable influence on how the ecosystem is being impacted by geopolitical developments. The third point is that the uncertainty at the physical hardware modality level is affecting other layers from supply chains to partnerships, from export controls regulations to investment decisions. The impact of geopolitics on quantum technologies is highly intertwined with the question of which physical realization of quantum systems will become the dominant modality. Finally, the question of how to secure future sensitive communications from the threat of quantum computers (via QKD and/or PQC) seem to have different answers for different regions, which might lead to further technical fragmentation.

1.6 Summary of the Landscapes of Quantum Technologies

This chapter covered five landscapes of quantum technologies; commercial, academic, technical, education and outreach, and geopolitical. Each subsection had several highlighted points in the end.

The commercial landscaping exercise revealed the following points:
(i) a clear lead of United States as a country vs. ongoing competition in Global North as regions,
(ii) clear gap between the Global North and Global South,
(iii) United States as the initial primary market for quantum computing, and
(iv) quantum technologies being subject to regular market forces (not like A.I.).

The academic landscaping exercise showed:
(i) quantum technologies having a steady increase in new publications for the last 25 years, unlike the A.I. or nanotechnology,
(ii) China having a strong presence in the academic publication and a centralized funding approach compared to other regions, and
(iii) relative lack of co-funding activities by top funding agencies between regions.

The technical landscaping exercise helped identify:
(i) there is a considerable diversity of research on how to best physically realize these technologies, all at different QTRLs, but no clear winners yet,
(ii) even though the assumption in the field since almost 2016 was that the cloud model will reign supreme, in the last two years things there has been a strong uptick in the on-premise quantum computers, no clear dominant operating model yet, and
(iii) quantum technologies as a wider umbrella term does not have a single technical trend but contains multiple trends for its different technologies.

The education and outreach landscaping exercise highlighted:
(i) a clear upward trend in almost every aspect of education and outreach related activities,
(ii) the formation of a new discipline-culture around these technologies, and
(iii) the importance of hype, expectations, and perception both by the public and within the professional communities.

Finally, from the geopolitical landscaping exercise we can ascertain the following points:
(i) the debate on open-close border collaborations due to geopolitical conditions is likely to become more important as geopolitical tensions rise and attitudes shift,
(ii) quantum technologies likely to have no actual relevance for military conflicts in the near term,
(iii) the uncertainty at the physical hardware modality level is affecting other layers and the impact of geopolitics on quantum technologies is highly intertwined with the question of which physical realization of quantum systems will become the dominant modality, and
(iv) the question of how to secure future sensitive communications from the threat of quantum computers (via QKD and/or PQC) seems to have different answers for different regions, which might lead to further technical fragmentation.

In terms of my own contributions to each of these landscaping topics, a list is given below.

Table **C1.6.1**: Publication contributions to the topics covered in Chapter 1

Section	**Title / In-text citation**	**Journal/Book/Conference**
Commercial	The landscape of the quantum start-up ecosystem (Seskir, et al., 2022a)	Published in *EPJ Quantum Technology*
Commercial	Global innovation and competition in quantum technology, viewed through the lens of patents and artificial intelligence (Seskir & Willoughby, 2023)	Published in *International Journal of Intellectual Property Management*
Academic	Subchapter 7.2.2: Milestones of research activity in quantum computing" (Seskir & Biamonte, 2024) in Chapter 7: Physics for secure and efficient societies (Barbato, et al., 2024)	Published as a book subchapter in *EPS Grand Challenges – Physics for Society in the Horizon 2050*
Technical	Building a quantum-ready ecosystem (Purohit, et al., 2024)	Published in *IET Quantum Communication*
Education & Outreach	Quantum games and interactive tools for quantum technologies outreach and education (Seskir, et al., 2022b)	Published in *Optical Engineering*
Education & Outreach	A Chronicle of Quantum Technologies in Game and Software Development (Skult, et al., 2024)	Published in *IEEE Computer Graphics and Applications*
Education & Outreach	Educating to the "Culture" of Quantum Technologies: A Survey Study on Concepts for Public Awareness (Seskir, et al., 2024b)	Published in *European Journal of STEM Education*
Education & Outreach	Games for Quantum Physics Education (Chiofalo, et al., 2024)	Proceeding in *3rd World Conference on Physics Education*
Education & Outreach	Why teach quantum in your own time: the values of grassroots organizations involved in quantum technologies education and outreach (Genenz, et al., 2025)	Published in *EPJ Quantum Technology*
Education & Outreach	Communicating Quantum Technologies in an Era of Mistrust and Misinformation (Goorney, et al., 2024a)	Published as a book chapter in *The Ecosystem of Science Communication in the Post-Truth Era*
Geopolitical	Exploring Pitfalls for Defence and Security by Narratives on Quantum Technologies (Seskir, et al., 2024a)	Proceeding in *NATO STO: Research Symposium on Quantum Technology for Defence and Security*

Chapter 2: Responsible Quantum Technologies

As described in the Prologue section, the direction of this thesis work changed in time since the first proposal, which was more focused on the futures of quantum technologies generally. The extensive work to cover the five different landscapes in Chapter 1 was supposed to support the entirety of the answers to the initial research questions posed, which were:

- How are quantum technologies imagined, envisioned and aimed to be realized in our current techno-societies?
- What are the possible path dependencies for future scenarios for the development of these technologies?

The highlighted points provided at section 1.6 were to be used to provide satisfactory answers to these questions and inputs from the responsible QT efforts play a minor role. Yet, my focus shifted due to changing circumstances, and the research questions were reformulated into:

- **RQ1:** How can responsible quantum technologies be imagined, envisioned and realized by the quantum technologies community?
- **RQ2:** What are the relevant topics and possible critical path dependencies for the development of these technologies responsibly?

To be able to address these questions, I took an action research approach, actively participating in many events as a speaker or panelist, and even organizing several events myself, with the practice of participant objectivation (Bourdieu, 2003) in mind. The list of these events can be found in Appendix A.

First, I need to unpack the question of what the ‘responsible’ in the responsible quantum technologies mean for me. In STI policy studies, there is a concept informally referred to as the control-promote dilemma, referring to the inherent tension between two competing objectives that policymakers face when governing emerging technologies. The dilemma of social control of technology (Collingridge, 1980), limits to social shaping of technology (MacKenzie & Wajcman, 1999), innovation-regulation paradox (Dewick & Miozzo, 2002), and the following literature on the RRI framework (Stilgoe, et al., 2013; Robinson, et al., 2020) and responsible innovation (von Schomberg, 2013) can be thought as efforts and proposals to address this dilemma.

For the context of this thesis, I adopted a somewhat general and abstracted approach utilizing my PhD training at and former publications from ITAS (Coenen & Grunwald, 2017; Coenen, et al., 2022), compared to more well-defined but constraining conceptualizations, and considered responsible quantum technologies as any effort that aims to take into consideration both potential benefits and advantages but also possible harms and risks of quantum technologies, aiming at a ridge walk between control and promote camps, with a clear understanding that there are different direct and indirect stakeholders when considering any technology and neither benefits nor harms are necessarily equitably distributed amongst these.

These led to my follow-up questions and the bulk of the content of this chapter. What is out there in terms of responsible quantum technologies? And how do the direct and indirect stakeholders of these technologies relate with them?

2.1 The (Short) History of "Responsible Quantum"

This section is actually a retrospective look at the history of the term "responsible quantum" building upon some analysis I conducted for a talk I gave at the IEEE Quantum Week 2024[28] as part of a workshop I co-organized with several others from the field on Responsible Quantum[29].

I started with two simple questions: Where and since when has the term "responsible quantum" been in use? How does it compare with other "responsible X"s? As the methodology, I utilized Scopus and Google searches for simple comparison purposes.

Table **C2.1.1**: Results returned from Scopus and Google searches as of Sept. 2024

Keyword	**Scopus**	**Google Search**
"Responsible quantum"	5 documents	9510 search results
"Responsible AI"	945 documents	21.700.000 search results
"Responsible nano*"	60 documents	9290 search results
"Responsible robot*"	47 documents	14.600 search results
"Responsible space*"	26 documents	42.100 search results

Figures 5 and 6 in the Prologue section are also from these search results. Figure 5 is reused as Figure **C2.1.1**. Figure **C2.1.2** shows the yearly distribution of Scopus publications for "responsible nano*", Figure **C2.1.3** shows the same for "responsible robot*", Figure **C2.1.4** for "responsible space*", and Figure **C2.1.5** for "responsible quantum." Some trends can be seen in these publications. First, Responsible A.I. is the most established and widely used keyword amongst these, and the ChatGPT bump from 2022 to 2023 can clearly be seen in the graph. Responsible Nano* seems to be on average the most stable one, with an average of three articles per year in the last two decades. Responsible Space* and Responsible Robot* also seems to have upward trends that pre-date the ChatGPT bump in the literature. Finally, Responsible Quantum seems to be rarely used in academic literature. From the data, the term appears to have originated out of the UK ecosystem around 2020, and later adopted by actors in the US, Canada, Australia, Germany, and Switzerland.

[28] https://www.rti.ox.ac.uk/event-ieee-quantum-week-2024/ (Accessed 23 May 2025)
[29] https://www.rti.ox.ac.uk/responsible-quantum-from-theory-to-practice/ (Accessed 23 May 2025)

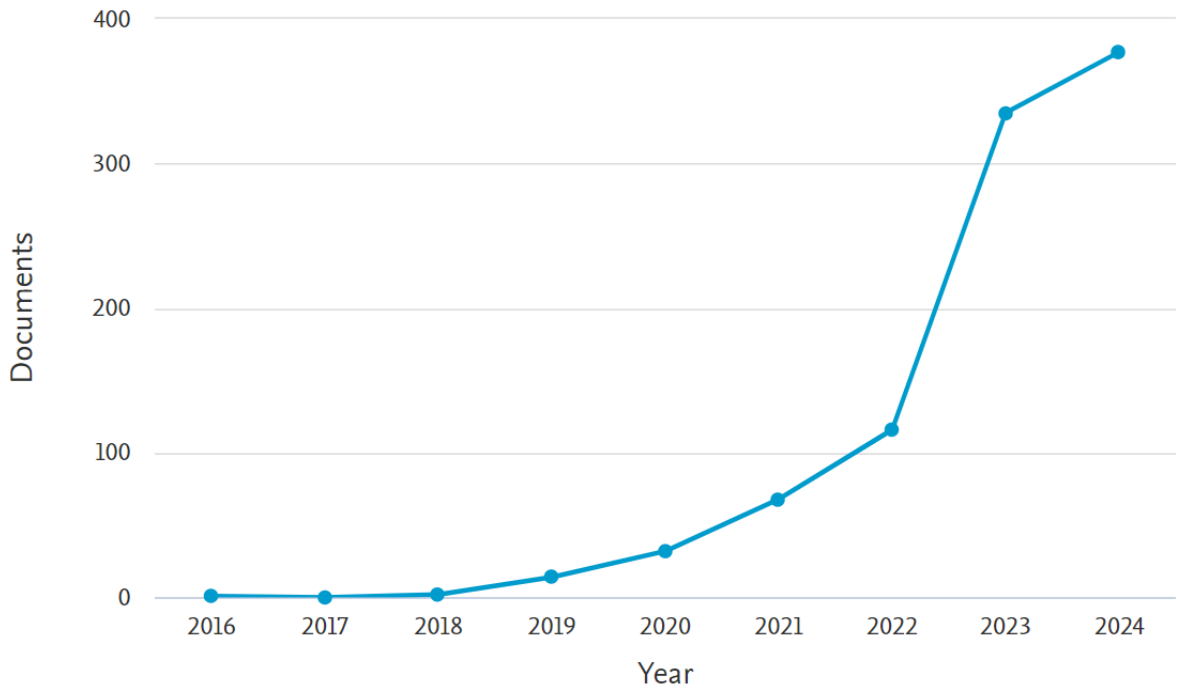


Figure **C2.1.1**: Number of articles published per year as of Sept. 2024 with keyword "responsible AI"

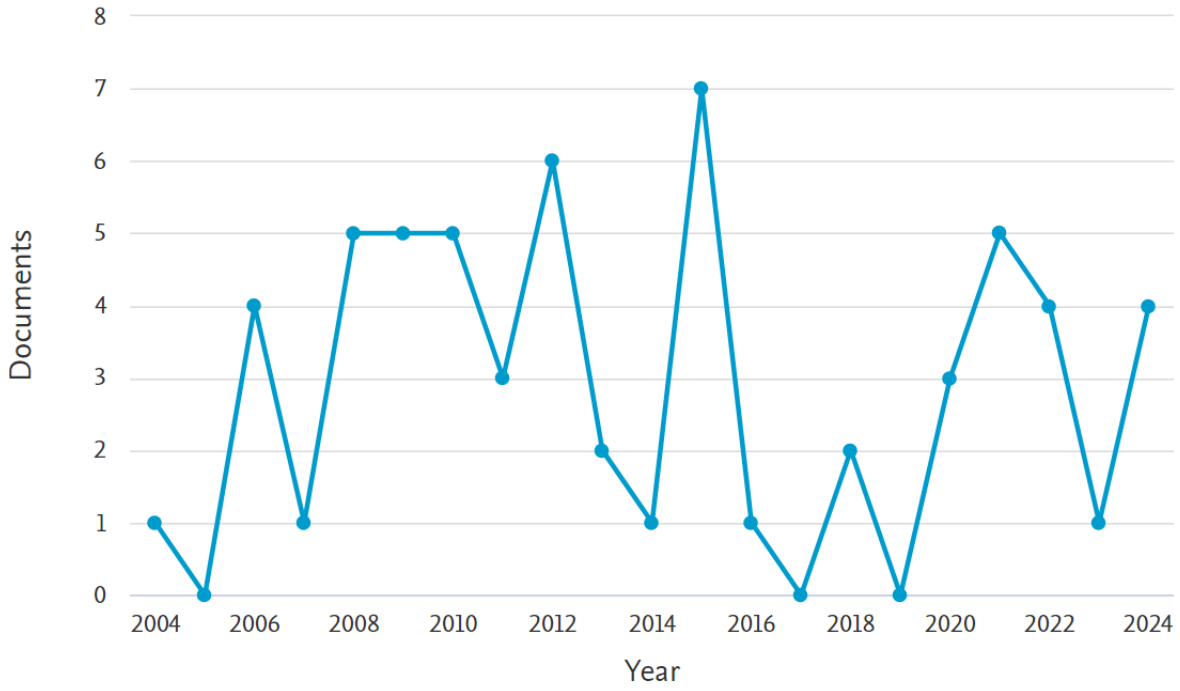


Figure **C2.1.2**: Number of articles published per year as of Sept. 2024 with keyword "responsible nano*"

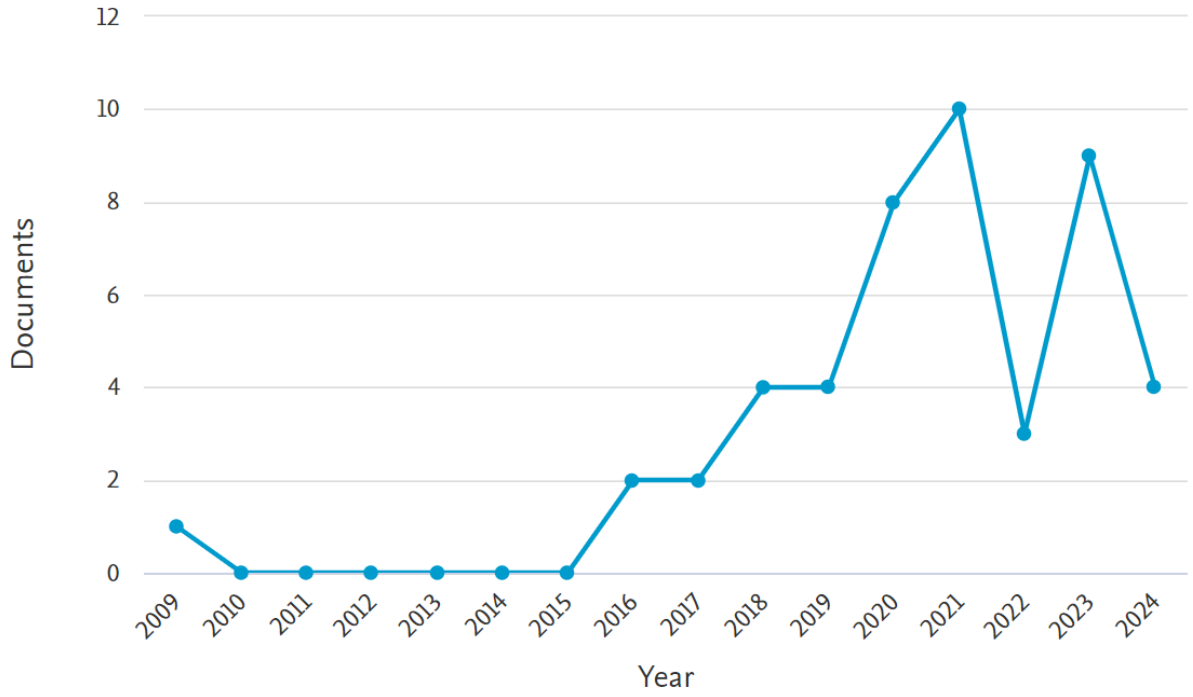


Figure **C2.1.3**: Number of articles published per year as of Sept. 2024 with keyword "responsible robot*"

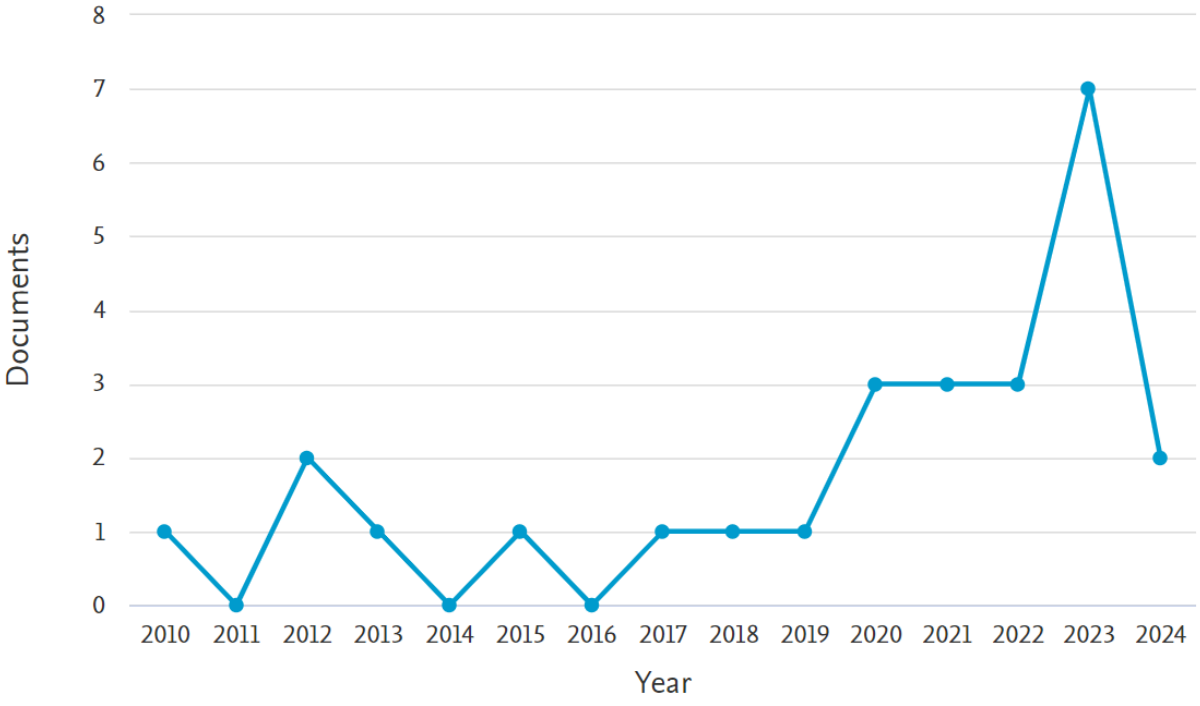


Figure **C2.1.4**: Number of articles published per year as of Sept. 2024 with keyword "responsible space*"

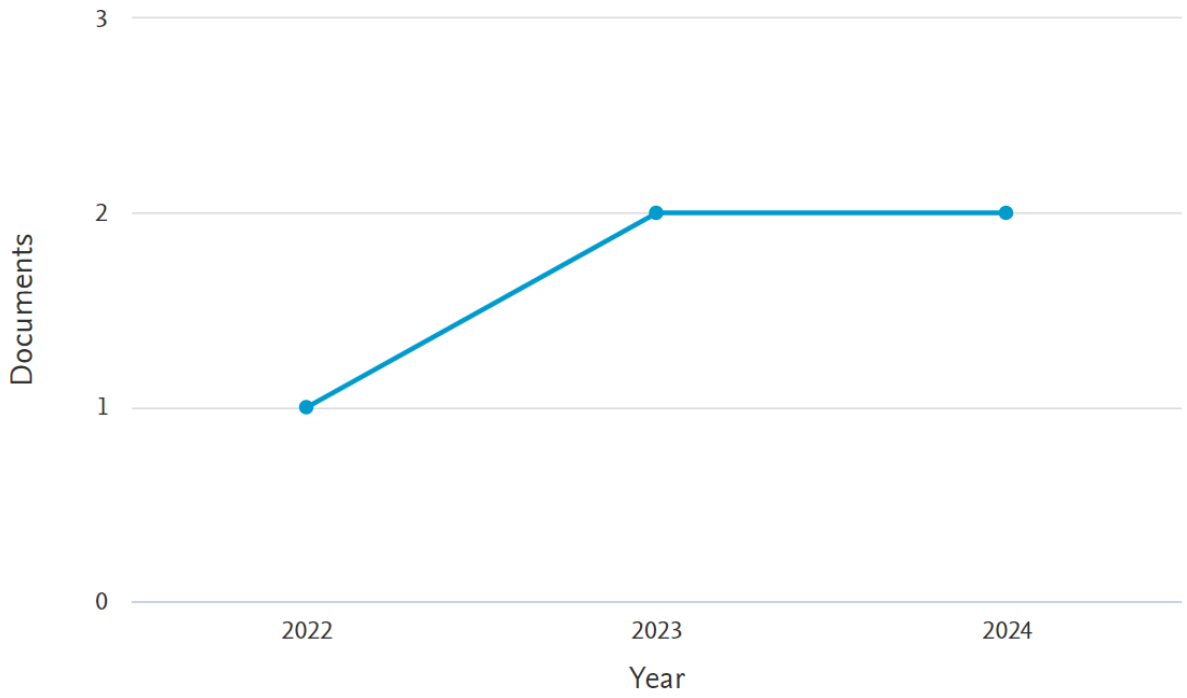


Figure **C2.1.5**: Number of articles published per year as of Sept. 2024 with keyword "responsible quantum"

I also gathered and listed the events organized with Responsible Quantum in their titles on Table **C2.1.2**. It is not an exhaustive list, but I would argue it is almost exhaustive. There might always be some events that are not easily accessible via online searches, but this is what one gets from the first 10 pages of Google. The list does not cover any event organized by the QDNL as they prefer to use the term "Quantum for Good"[30], which seems to be also the route taken by Microsoft (Troyer, et al., 2024). Meanwhile, IBM seems to have adopted the term Responsible Quantum at least since mid-2022[31] and recently making it more publicly visible (Wolf-Bauwens & Mandelbaum, 2024).

There are also a couple of institutions that seem to be forming up using the phrase Responsible Quantum. In the US, the Stanford Center for Responsible Quantum Technology[32] under the Law School is an example. In Canada, the Centre for Responsible Quantum Innovation and Technology (CRQIT)[33] under the Quantum Algorithms Institute in British Columbia is another one. And finally in the UK there is the Responsible Quantum Industry Forum[34] being formed under the UK National Quantum Computing Centre (NQCC).

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30 https://quantumdelta.nl/news/new-quantum-for-good-partnership-initiative-between-unicc-and-quantum-delta-nl (Accessed 23 May 2025)

31 https://docs.quantum.ibm.com/responsible-quantum-computing (Accessed 23 May 2025)

32 https://law.stanford.edu/press/sls-launches-a-first-of-its-kind-center-for-responsible-quantum-technology (Accessed 23 May 2025)

33 https://www.qai.ca/centre-for-responsible-quantum-innovation-and-technology (Accessed 23 May 2025)

34 https://www.nqcc.ac.uk/events/responsible-quantum-industry-forum-2024/ (Accessed 23 May 2025)

Table **C2.1.2**: A list of events organized as of Oct. 2024 with Responsible Quantum in title

Organizer(s)	**Title**	**Country - Year**
Karlsruhe Institute of Technology	Responsible Quantum Technologies (ResQT) 2021	Online - 2021
Tortoise Media	Responsible Quantum Summit	UK - 2022
Karlsruhe Institute of Technology	ResQT2022	Germany - 2022
QIDiS (ID Quantique, CSEM, IBM Quantum, and others)	Responsible Quantum Technologies in Switzerland	Switzerland - 2023
OECD	Future in flux? Global issues and national strategies for responsible quantum technology development	Online - 2023
Stanford Law School (SLS)	1st Annual Stanford Responsible Quantum Technology Conference	US - 2023
Karlsruhe Institute of Technology	ResQT2023	Germany - 2023
IBM	Computing Responsibly in the Era of Post-Quantum Cryptography	US - 2023
2023 IEEE International Conference on Quantum Computing and Engineering (QCE)	Developing Responsible and Ethical Quantum Computing for Societal Benefit	US - 2023
Stanford Center for Responsible Quantum Technology	2nd Annual Stanford Responsible Quantum Technology Conference	US - 2024
2024 IEEE International Conference on Quantum Computing and Engineering (QCE)	Workshop on Operationalising Responsible Quantum Computing	US - 2024
Karlsruhe Institute of Technology	ResQT2024	Germany - 2024
RSIS, SGInnovate, CQT, Karlsruhe Institute of Technology	ResQT: Impact of Geopolitics in the Indo-Pacific Region	Singapore - 2024

On June 7, 2024, the United Nations proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ). According to the proclamation, this year-long, worldwide initiative will be observed through activities at all levels aimed at increasing public awareness of the importance of quantum science and applications[35].

[35] https://quantum2025.org/en/ (Accessed 23 May 2025)

The IYQ is also expected to spur a number of responsible quantum events. There are already preparations, such as a workshop on Responsible Quantum Innovation supported by the NSF in the US[36]. The ResQT2025 to be organized in Karlsruhe, the third responsible quantum workshop at IEEE Quantum Week 2025, the 3rd Annual Stanford Responsible Quantum Technology Conference, and so on.

All these points considered above provide a somewhat clear picture, serious activities into Responsible Quantum are relatively new, with a (short) history of not even five years. Yet, they have been multiplying and growing. There are centers being formed, events with certain continuity between years are forming up, and the academic literature is (even though it is still nascent) starting to accumulate. The next section gives a wider perspective on how these efforts are being studied and realized by different stakeholders in the community.

2.2 How Responsible QT is being studied and realized?

The first thing that needs to be clarified in this section is that the efforts I bundle up under the Responsible QT umbrella goes beyond the mere use of the term itself. In addition to "Responsible Quantum" and "Quantum for Good", terms such as "Quantum Ethics" are also being used by some in the community. There was a short video documentary titled "Quantum Ethics | A Call to Action"[37] in 2021 featuring some CEOs of quantum computing companies that was even covered by the Wall Street Journal at the time (Castellanos, 2021). There were also some grassroots initiatives on the topic such as the Quantum Ethics Project[38], institutional centers such as the Innsbruck Quantum Ethics Lab (IQEL)[39], academic publications on ethical quantum computing (Perrier, 2022a; Possati, 2023), a concept note of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) on the ethics of quantum computing at UNESCO (2024), and even some efforts on quantum ethics education research (Meyer, et al., 2022; Arrow, et al., 2023). There are centers and labs with similar efforts as well, one example is the Centre for Quantum and Society (CQS)[40] launched by the QDNL in 2022 that brings together the Dutch efforts under the Action Line 4, which focuses on the "Societal Impact of Quantum Technologies." Another example is the TUM Quantum Social Lab[41] in Germany that was also launched in 2022 which aims at envisioning implications of quantum technologies for society, economy, and governance.

There has also been some gray literature generated on the topic, such as a couple of extensive white papers published out of the Oxford Responsible Technology Institute (RTI) (Ten Holter, et al., 2021; Ten Holter, et al., 2024), a participatory roundtable exercise report by KPMG Australia & Sydney Quantum Academy (2022), and a comprehensive stakeholder mapping exercise for a "*...trusted, ethical, and inclusive quantum ecosystem*" by the Australian CSIRO (Baruwal Chhetri, et al., 2024). This list is not exhaustive and will grow considerably in time.

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[36] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2427775 (Accessed 23 May 2025)
[37] https://www.youtube.com/watch?v=5qc7gpabEhQ (Accessed 23 May 2025)
[38] https://www.quantumethicsproject.org/ (Accessed 23 May 2025)
[39] https://www.uibk.ac.at/projects/iqel/index.html.en (Accessed 23 May 2025)
[40] https://quantumdelta.nl/centre-for-quantum-and-society (Accessed 23 May 2025)
[41] https://quantumsociallab.de/ (Accessed 23 May 2025)

All these terms are sometimes used interchangeably by different actors and one can categorize them together under the same umbrella of a particular type of governance efforts, trying to address the control-promote dilemma from different perspectives. One of the most active parties in this regard has been the World Economic Forum (WEF), which published reports titled Quantum Computing Governance Principles (Coates, et al., 2022), Transitioning to a Quantum-Secure Economy (Beato, et al., 2022), Quantum Economy Blueprint (Richdale, et al., 2024), and Quantum for Society (Converso, et al., 2024) in the last two years. There were other efforts as well, such as the quantum governance stack proposal by Elija Perrier (2022b) and some proposals by Hoofnagle & Garfinkel in their book Law and Policy for the Quantum Age (2022).

One emerging trend, following the developments in the A.I. ethics and responsible A.I. field, is the formulation of principles. The “Quantum Technologies and Society: Towards a Different Spin” manifesto by Coenen et al. (2022) recommends quantum technologies to be made more Comprehensible, Specific, Open, Accessible, Responsible, Culturally embedded, and Meaningful. The WEF Quantum Computing Governance Principles (Coates, et al., 2022) highlights Transparency, Common good, Accountability, Inclusiveness, Equitability, Non-maleficence, and Accessibility as core values. The “Ten principles for responsible quantum innovation” paper by the Transatlantic Quantum Forum members (Kop, et al., 2024) promotes ten principles around three categories they name as Safeguarding, Engaging, and Advancing (SEA), with a mix of ten topics, aims, and RRI-values.

These categorization and prioritization efforts of the principles also lead to more impactful outcomes. For example, the Microsoft paper on “Quantum for Good” (Troyer, et al., 2024) building upon their Responsible AI principles (Microsoft, 2018) focuses on three priorities for safe and responsible quantum technologies; impact, use, and access.

As quantum computing is the primary focus of Microsoft, they focus on these priorities with respect to that particular technology and list their relevance in the following form (p.2):

- **Impact:** Ensure quantum computing benefits all of humankind by developing quantum solutions to solve critical, global problems.
- **Use:** Protect against malicious use by accelerating the deployment of quantum-safe cryptography and developing governance processes and controls for the responsible use of quantum machines.
- **Access:** Democratize the potential for economic growth across all of society through skilling, workforce and ecosystem development, and digital infrastructure.

These, although they might look as quite general statements, focus on some relevant pain points and contestation areas in the field of quantum computing. For example, the point on developing quantum solutions to solve critical, global problems is addressing a point of discussion in the community on “who are we building quantum computers for” (Figure **C2.2.1**,

Arrow & Marsh, 2023), which even leads to the question “should we build quantum computers at all?” (Chen, 2022).

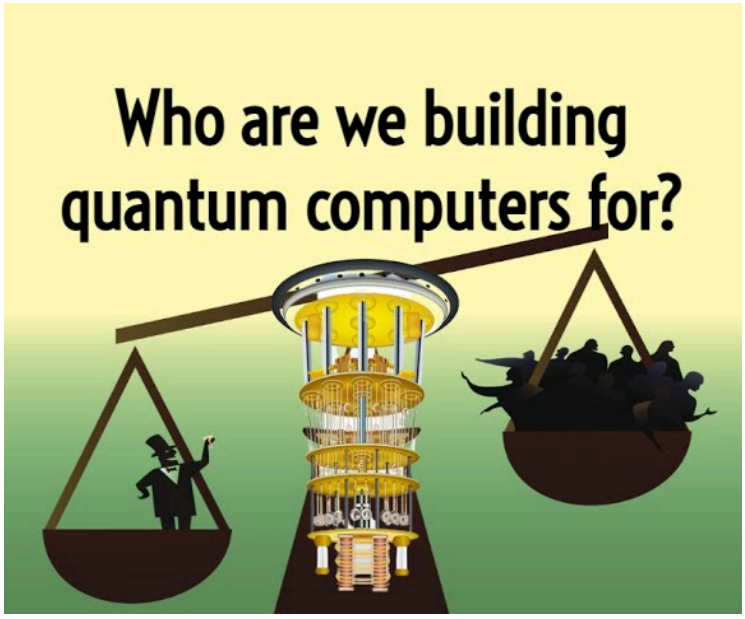


Figure **C2.2.1**: A slide from the Quantum Ethics lecture series (Arrow & Marsh, 2023)

The point of use is also quite timely and relevant. In the paper, they state that QKD is a more nascent quantum-safe technology that cannot be considered secure on its own (p.7) and that migration to quantum-safe security measures relying on PQC solutions is the most meaningful proactive risk management strategy industry and governments can apply (p.8). Troyer himself even said[42] that he considers presenting QKD as an alternative to PQC to be irresponsible.

Finally, the point about access, democratization, and skilling has been of high relevance for the community since IBM launched their first publicly available quantum processor unit in May 2016 (Vu, 2016) and a considerable ecosystem of enthusiasts started forming up around these devices. In our paper titled “Democratization of quantum technologies” (Seskir, et al., 2023a) we covered the conceptualization of democratization and its relation to access (pp.2-6), the efforts in democratization of quantum computing (pp.6-9), narratives supporting and against democratization (pp.9-13), and the relationship between access and participation (pp.13-15). The relevance of discussions on skilling, workforce and ecosystem development in the quantum technologies domain is already covered in section 1.4 of this thesis work.

The relation between responsible QT efforts and analysis of narratives is also important. As briefly covered in our democratization paper (pp.9-13), narratives in quantum technologies have been a deliberation ground for a while now. Discussions on the relationship between quantum technologies and public good (Roberson, et al., 2021), responsibility (Roberson, 2023), and hype (Roberson, et al., 2023) have been problematized in the literature. And studies covering a comprehensive analysis of TEDx talks (Meinsma, et al., 2023) and Dutch newspapers

[42] During the panel after his talk at the Workshop on Operationalising Responsible Quantum Computing at 2024 IEEE International Conference on QCE.

(Meinsma, et al., 2024) highlight that there is a preference in the media to focus on potential benefits while the risks are not really covered with similar rigor.

There have been studies covering some other relevant topics that tie to the responsible QT debates. One example is on the global mobility discussions of researchers in an article wittily titled “Quantum researcher mobility: the wonderful wizard of Oz who paid for Dorothy's visa fees” (Malik, et al., 2022), where the issues such as exorbitant visa fees that are non-eligible for reimbursement, the problems with short-term contracts, visa renewals, and funding agency rules have been investigated, topics which are mostly invisible and not easily imaginable by resident academics or those from common and shared visa zones such as Schengen. Another good example is the investigation of the potential impact of quantum technologies on the human rights domain. In this literature, Ritter (2021) highlights the rarity of open dialogue among technology and legal stakeholders regarding how to innovate and govern, and Krishnamurthy (2022) stresses how governments can create the conditions for successful self-regulatory and multi-stakeholder initiatives in order to address the human rights impacts of quantum technologies. There have also been more recent publications by Ot van Daalen on developing a human rights compatible governance framework for quantum computing (2024a, 2024b).

Finally, there has been the question of who are the direct and indirect stakeholders of quantum technologies. The answer to this question is highly relevant to the efforts on access and democratization, as for any kind of deliberative or participatory practice one needs to have a good understanding of the stakeholder landscape (Seskir, et al., 2023a, pp.3-6). This is one of the reasons why an organization like CSIRO in Australia focusing on responsible innovation in quantum technologies commits resources to stakeholder mapping efforts (Baruwal Chhetri, et al., 2024). There have been attempts in the literature on this (Perrier, 2022b), including ours (Umbrello, et al., 2024). One common outcome of all these efforts is that the quadruple helix model widely used in STI policy making (Carayannis & Campbell, 2009) does not suffice for categorization of stakeholders in the quantum technologies domain for participatory or deliberative exercises. Another outcome is that for different quantum technologies, such as computing, sensing, networking, etc. there are not just different stakeholders but possibly different groups of stakeholders. One example is cybersecurity, where as a relevant topic with respect to quantum computing it comes into play not just from academia, but also from industry, public authorities, and civil society (Chaos Computer Club[43] as an example), similarly for quantum communications, but not really for quantum sensing. A more diversified and nuanced understanding of the stakeholder landscape is advisable, as analyses relying on traditional stakeholder groups in the STI policy approach (academia, industry, public authorities, and civil society) might result in obfuscation of many potential inter-and intra-stakeholder group conflicts.

Topic oriented self-organization of stakeholder groups in quantum technologies provides a valuable opportunity to identify which topics are seen as highly relevant for responsible QT efforts by the quantum community itself. The self-organized groups in education and outreach efforts such as QWorld and OneQuantum have already been covered in the previous parts of

[43] https://media.ccc.de/v/37c3-12034-the_impact_of_quantum_computers_in_cybersecurity (Accessed 23 May 2025)

this thesis work, but there have been self-organizing efforts beyond just education and outreach in the community, focusing on topics ranging from diversity to sustainability.

There have been several groups on gender issues and female participation in quantum technologies such as Women in Quantum Development (WIQD)[44] targeting professional women in the field, Girls in Quantum[45] aimed at increasing young female participation (even high school students) into quantum computing efforts, and Women in Quantum[46] which provides mentorship (and menteeship) opportunities to women in the field. Increased activity on this topic in the last few years culminated into the publication of a joint declaration by many women in the field titled "Women for Quantum -- Manifesto of Values" (Beige, et al., 2024), which had around 200 "First endorsers" (pp.5-9), and a list of values and goals the authors (and endorsers) identify with.

Similarly, there have been several groups on sustainability topics. The Quantum Energy Initiative (QEI) was launched in August 2022 with a Manifesto[47] with the opening statement "*As quantum technologies drive strong expectations from governments and industries, we believe a responsible way of deploying them must include the study of their potential for energy savings and contained environmental footprint*." and a publication titled Quantum Technologies Need a Quantum Energy Initiative (Auffèves, 2022). This manifesto gathered around 250 signatures from domain experts between August 2022 and January 2023, and QEI organized its first dedicated workshop in Singapore in November 2023[48]. The second workshop is going to take place in Grenoble, France in January 2025. Although QEI is rather active and well-known in the field, it is not the only one. There are others, such as the Q4Climate[49] initiative which aims at gathering "...*the research and industry communities together around quantum and climate sciences with the aim of developing new insights into how we may reduce the pace and impact of climate change*." They published a preliminary assessment of quantum technologies for climate change in 2021 (Berger, et al.), and have been organizing workshops in different venues (such as the QWC 2024 event in D.C.). Finally, there have been sustainability and climate oriented efforts formed under already established communities, such as the PushQuantum Climate[50] which is formed within the PushQuantum (a Munich-based student-led quantum grassroots organization).

Equity, Diversity, and Inclusion (EDI) has also been a topic where community based efforts are found. One example is the EDI working group under the Quantum Flagship that seeks to "*...address imbalances in the European quantum community*"[51]. Another is the Q-turn workshops[52] organized in 2018 and 2020 (Sainz, 2022), which aimed "...*to foster an inclusive community and highlight outstanding research that may be under-appreciated in other*

[44] https://www.wiqd.nl/ (Accessed 23 May 2025)
[45] https://girlsinquantum.com/ (Accessed 23 May 2025)
[46] https://onequantum.org/women-in-quantum/ (Accessed 23 May 2025)
[47] https://quantum-energy-initiative.org/manifesto-archive/ (Accessed 23 May 2025)
[48] https://qei2023.sciencesconf.org/ (Accessed 23 May 2025)
[49] https://q4climate.github.io/ (Accessed 23 May 2025)
[50] https://www.pushquantum.tech/sustainability (Accessed 23 May 2025)
[51] https://qt.eu/working-groups/equity-diversity-and-inclusion (Accessed 23 May 2025)
[52] https://qturnworkshop.wixsite.com/2018 (Accessed 23 May 2025)

high-impact venues due to systemic biases." Increased level of activity in this domain also led to formation of more structured organizations such as the NGO Diversity in Quantum (DiviQ)[53].

Most of these efforts rely on contributors committing their time voluntarily, as funding into these topics are both scarce and are sometimes highly problematic even when there is available funding. For example, in terms of gender-equality specific topics, a Gender Equality Officer from a prestigious German university said in a panel that she had to return almost her entire yearly budget back to the university as the conflicting rules and regulations between the university and the state rendered spending of those resources impossible. We experienced a similar issue when organizing one of our ResQT workshops, when a speaker joining us from an Italian research organization asked for childcare support as reimbursement, we found out that our university only provided that kind of support for our own employees. And, she found out that her institution only provided support of that kind for incoming guests and not for their employees. In the end, even though both our side and her side had available funding and were willing to provide support, she was not able to receive childcare support for the workshop. Such regulatory difficulties and conflicts in the gender equality domain are being mapped out by the Modifying Institution by Developing Gender Equality Plans[54] (MINDtheGEPs[55]) H2020 project, but given the sheer size of the European higher education and research ecosystem, it is highly unlikely that the issues can be resolved swiftly.

In terms of how responsible QT efforts are being studied and realized, there are three points that I will aim to address in the following Chapter. First is that it is a nascent topic, starting to get traction only in the last couple of years. Yet, as we know from A.I. ethics (Figure 6) and responsible A.I. (Figure 5/**C2.1.1**) domains, these topics tend to pick up quickly if the corresponding technology also starts accelerating. The second point is the emerging institutionalization of research and activities in responsible QT, ranging from academic centers and labs such as the Stanford and TUM ones to CQS and IQEL, to industry ones such as IBM Responsible Quantum Computing efforts to UK Responsible Quantum Industry Forum, to more workshop-based gatherings such as ResQT and IEEE. The final point is the extent of self-organization and the "the call is coming from inside" mentality for such efforts in the quantum technologies community. From trying to reign in the hype (to the point where sometimes you can find complaints of "hype policing" in the community (Phillips, 2024)), to promoting gender equality (Beige, et al., 2024), diversity (Sainz, 2022), and sustainability (Auffèves, 2022), the community has been putting in the effort to not repeat the previous mistakes, especially those of A.I. and wider efforts around digitalization.

2.3 Reactions to Responsible QT efforts

It is quite difficult to find publications or people that explicitly come up against such efforts, nobody likes to put their name on a paper or news article calling for unethical or irresponsible development and use of quantum technologies. However, this doesn't mean that everybody is

[53] https://www.diviq.org/ (Accessed 23 May 2025)
[54] https://cordis.europa.eu/project/id/101006543 (Accessed 23 May 2025)
[55] https://www.mindthegeps.eu/w/home/ (Accessed 23 May 2025)

onboard with these responsible and ethical quantum technologies efforts. In this section, I will go over some explicit examples of some reactions to responsible QT efforts and summarize their counter-arguments. I will mostly rely on observational and personal data and anecdotes, since there is only a few publicly available content on this.

One such content is a 23 minutes long YouTube video by a group of researchers at the NYU Quantum Technology Lab (2021) reacting to the “Quantum Ethics | A Call to Action” video documentary mentioned previously, which is 13 minutes long. In the video, there are six researchers from the lab, watching and reacting to the documentary. I downloaded the transcription of the video to provide some quotes.

The documentary consists of several start-up CEOs and quantum computing researchers talking about potential benefits and risks of quantum computing, and the need for responsible and ethical considerations. As an early reaction, someone from the lab group responds by saying “*I don't really think it's our job or their job to discuss the possible dangers, like, if we should do it or not. We just find a way to make it happen and we don't care if it's okay or not. Just do it because it's cool*.”

Another point discussed in the documentary is about the potential of quantum computing to increase inequalities and that democratization of these technologies are necessary, to which someone from the group responds by saying, “*Students in advanced countries can access smartphone marketing right now while students from poor countries are only seeing classical computer right now so. How then do they access the quantum company? So that, that imbalance is already there. …and even the democratization is also there, because the democratization tells me, I can buy this or I cannot buy this*.” where another researcher in the video responds by saying “*You are such a capitalist*.” and they laugh.

Following the point on “*We know that the genie is going to be unlocked.”* argument in the documentary, “*Yeah, that's like hype building, we don't know if the genie will be unlocked, there might never be any reliable scalable quantum computer ever. There is such possibility… and maybe all the funding money will be wasted. She's so sure. She says we are sure the genie will be unlocked. No, we are not sure. There is a possibility it will never be unlocked. Yeah, there is a chance for that and that's why it's science, it's risky, we don't know if it will work or not, it's unknown. It's not basic, it's not like building a lego castle, like just following the instructions. No, we don't know how to do it and maybe we will never know. There is such possibility.*”

Near the end, someone in the video reiterates the point, “*I advocate the attitude that you should do quantum because it's awesome and not because you can do something with it*.”

Their arguments can be summarized as; overhyping quantum computing's readiness and impact is premature, and existing ethical frameworks for technology can guide advancements in quantum technologies without creating unnecessary restrictions on an already risky endeavor.

These sentiments are shared by others in the community as well. A personal example in this is that during the Workshop on Operationalising Responsible Quantum Computing at 2024 IEEE QCE, after the presentations someone in the audience, who was a co-founder of an influential mid-sized quantum computing company took the microphone and said:

"*I would like to strongly disagree with all the wishlist of arguments where I see absolutely nothing concrete. You know, if we are going to ban the wheel because it took a lot of jobs, if we are going to ban six months of AI as proposed in the US because we are the good doers while the wrongdoers advance more AI to harm more. You know, so or are we going to make a, you know, hand in hand singing in the rain, we are the good guys controlling the quantum computers while the quantum nuclear bombs arrive from the other side… I don't get the point of how this wishlist of we should all be good, to kill people is bad yeah, there are millenia of wars and you don't go to the war areas and you say wars are bad. I mean, wars happen. I am not saying that's fantastic, but I don't see in everything I heard today concrete measures that are viable, realistic, and working, you know. I also know, love is wonderful, friendship is wonderful, you know, good people are wonderful, ethics is wonderful. But I read the newspaper everyday, like you do, right? And I don't see those wishes are transforming into facts at all. So, I would like to really challenge [to find] concrete actions that are working beyond telling the people, the others, you should be as good as me because read history, right? That does not work. That's a fantasy*."

Panelists responded to his challenge to find concrete actions, but mainly reiterated the point that the topic is rather new and it is not easy to come up with concrete proposals at this stage. He respectfully listened, nodded, and when the next audience member started asking their question, he got up and left the room.

This encounter reminded me of the "...*ethics gets you killed.*" reply I got at the ENDR Warsaw event, where ethics is primarily understood by actors in the field as additional (and sometimes unnecessary) restrictions and constraints. A similar discussion took place at our table during the networking part of the Bitkom Quantum Summit 2024, which was right after the session titled "Building a National or Regional Quantum Strategy - Responsibly". A couple of researchers at the table complained about values and responsible quantum efforts because they were distracting from making the technology work and causing Europe to lose the "race." They said "*we need to have the technology working first*". There was even an argument about being very much against transparency as a value because Europe is behind. They were also very critical of the IBMs contractual obligation approach (which puts limits on applications that can be run by the receiving party of their quantum computers), arguing that suing their clients would definitely not stop them from using the devices for nefarious purposes.

There were also more directly constructive reactions to responsible QT efforts. For example, there was a blogpost titled "Is it too early to talk about responsible quantum technologies?" (Cabaj, 2023), which was supportive but promoted the question in the title. Another widely circulating argument, which can also be found in "Ethics of Quantum Computing: an Outline" (Possati, 2023) is whether the ethical issues posed by quantum technologies are fundamentally

different from those associated with other advanced technologies and could existing ethical frameworks and guidelines be sufficient to address concerns related to quantum technologies. Another commonly raised concern is that imposing ethical guidelines and responsible innovation frameworks too early in the development of quantum technologies could stifle innovation and might lead to unnecessary bureaucratic hurdles (Ezratty, 2022).

As mentioned in the introduction of Chapter 2, the responsible QT discussions are efforts partially to come up with a response to the control-promote dilemma. The developers of the technology (researchers and industry) usually focus on the promote aspect of STI policy making and governance efforts, while seeing the control dimension as something that comes after a technology has already emerged. Yet, unknown to most of them, the world of emerging technologies governance is moving towards a more anticipatory governance approach[56]. This doesn't necessarily mean that responsible or ethical quantum efforts are automatically called for though, and there is validity in the points raised by the critics above:

(i) putting premature ethical constraints might hinder progress and put potential benefits at risk,

(ii) there are already existing frameworks for technology governance and for quantum technologies those might suffice, and

(iii) the responsibility measures proposed (such as principles and values) usually lack concrete or viable actions that can be adopted in technology development practices.

If we accept that quantum technologies will happen and they will deliver revolutionary capabilities, then an anticipatory governance approach in containing the potentially sizable negative impacts of these technologies makes sense. However, if there is a chance that quantum technologies may not materialize or not deliver revolutionary capabilities, then putting additional ethical or regulatory constraints over them might cause them to be not developed, hence depriving the society of the potential benefits that can arise from introduction of these technologies to the markets. The critics have a point in arguing that hype and overpromising with unjustified confidence might lead to skewed results in governance. Those critics also have a vested interest in making these claims, as most of their careers and success rely on making these technologies work. They don't see much skin in the game by the regulators, as the regulators (or those who are calling for regulation) might move on to the next big thing to be regulated while the researchers, entrepreneurs, and investors who have committed themselves to quantum technologies might suffer considerably from their failure to materialize. One clear example of this for me was when a senior legal officer from a large quantum computing start-up described their interaction with a US senator to me, who had allegedly said "I would see all American quantum companies go bankrupt if that would keep this technology away from China's hands." One might see the point of those NYU Quantum Technology Lab guys about overhyping the promises of quantum computers actually resulting in highly stringent export controls regulations that are already causing considerable compliance costs and suffocating start-ups.

[56] https://www.oecd.org/en/topics/anticipatory-governance.html (Accessed 23 May 2025)

The second point about already existing frameworks for technology governance both has validity and it is not an argument against responsible QT efforts but an argument for shaping those efforts in a certain way. Although there are already existing frameworks for technology governance, their implementations for quantum technologies is not a clear-cut case. An example is from the fair machine learning domain where explainability is an important principle. For quantum machine learning models, the regular tool set developed for classical machine learning models are not directly applicable and require considerable additional technical research and work (Perrier, 2021), they might even not be applicable at all and need to be revised, altered, and expanded to cover quantum machine learning. This may apply to the implementation of many frameworks we have ranging from human rights (van Daalen, 2024a, 2024b) to privacy and online safety (NSA, 2024), and others. Introduction of quantum technologies might not require inventing new frameworks, but identifying how to fit quantum technologies to the existing frameworks or how the introduction of quantum technologies would require alterations to the existing frameworks are still highly relevant research and activity points. An example I use for this case frequently is the so to speak Chatkontrolle debates in the EU (Breyer, 2024), where introduction of such regulations without considerable changes to them would render a quantum internet infrastructure either illegal or useless (due to mandatory additions of legally enforced backdoors to the end-user devices).

The last point is also quite valid, yet I believe this is mostly an area for growth, deliberation, and adopting new practices in technology development processes. For example, an expert in value sensitive design once explained it as today, engineers consider safety requirements as a core part of their duties, they are not only focused on making their products work, their products should also be safe. A similar shift in mindset should happen for other values as well in time. It is still unclear on who should bear the burden here in terms of moral division of labor to make these proposed measures concrete and viable.

In one of our ResQT workshops, the researcher from QEI who was explaining the issue of energy efficiency and resource consumption of quantum technologies said “somebody should be responsible for that, it is not me, but somebody should be.” There was fierce response from the social scientists in the room, claiming that of course it should be his responsibility to implement these principles. In my opinion, this would not work, as the social scientists assume the researchers possess the knowledge, the capability, and the mandate to implement these principles, when in fact researchers working on an emerging topic (such as quantum technologies) rarely have the necessary knowledge and capability on translating values and principles into design constraints, or the mandate to do so from their organizations or funding agencies. On the other hand, the social scientists rarely have the domain knowledge nor the access to develop those concrete and viable responsibility measures. It is very rare for a social scientist working on quantum technologies to ever see a functioning physics lab or a social scientist working on A.I. to ever see a server farm or actually train any models. This is something that needs to be developed with a shared responsibility and labor amongst the actors in the field, and although some cues can be taken from previous experiences (such as nano or A.I.) it is not something readily available out there that can be simply copied and implemented for quantum technologies.

2.4 Summary of Responsible Quantum Technologies

This chapter covered three sections, the history and landscape of responsible QT efforts, how these efforts are being studied and realized, and the skeptical reactions from the community towards these efforts. The outcomes of this chapter that will be utilized in the next chapter can be summarized as below.

In terms of how responsible QT efforts are being studied and realized, there are three points:

(i) Responsible QT is a nascent topic, starting to get traction only in the last couple of years. It might pick up quickly, but it is too early to tell.

(ii) There is an increasing amount of institutionalization of research and activities in responsible QT, ranging from formation of centers and labs, to a growing number of yearly organized events.

(iii) There is a considerable level of self-organization in the quantum community on some socially relevant topics that go beyond education and outreach efforts, such as hype, gender equality, EDI, and sustainability.

And there are three points raised by the critics of responsible QT efforts:

(i) Putting premature ethical constraints might hinder progress and put potential benefits at risk.

(ii) There are already existing frameworks for technology governance and for quantum technologies those might suffice.

(iii) The responsibility measures proposed (such as principles and values) usually lack concrete or viable actions that can be adopted in technology development practices.

Of course neither of these lists are exhaustive, but I believe they cover the top three most relevant points.

In terms of my publication contributions to the discussions of this chapter, a list is given below.

Table **C2.4.1**: Publication contributions to the topics covered in Chapter 2

Title / In-text citation	**Journal Publication**
Democratization of quantum technologies (Seskir, et al., 2023a)	Published in *Quantum Science and Technology*
Communities of quantum technologies: Stakeholder identification, legitimation and interaction (Umbrello, et al., 2024)	Published in *International Journal of Quantum Information*

Chapter 3: Conditional Futures of Responsible Quantum Technologies

In futures studies there are different established approaches when dealing with emerging technologies such as scenario planning (Schwartz, 1991) and strategic foresight (Hines & Bishop, 2015), and for guiding the development trajectory of such technologies, concepts and methods such as preferred futures (Inayatullah, 2004) and backcasting (Robinson, 1990) have been utilized since decades. In the field of technology assessment, there are approaches such as constructive technology assessment (CTA) (Schot & Rip, 1997) and transformative vision assessment (Schneider, et al., 2023).

The outcomes of this chapter and the thesis work can be used as input for these practices, they can provide useful insights for scenario planning and strategic foresight exercises, or guide the development and formation of CTA or transformative vision assessment workshops for quantum technologies. In these regards, this thesis does not provide a complete and final result to the questions of what a responsible quantum future looks like or how it can be reached. Instead, it is a comprehensive exploratory effort on identifying how these responsible QT futures can be formulated and what the critical conditions and path-dependencies for responsible development of these technologies are. To achieve this goal, this chapter has two objectives:

(i) reformulate the points highlighted in the previous chapters to identify interconnections between the current landscape of quantum technologies and responsible QT efforts,

(ii) and identify the critical conditions for responsible QT futures to map out path-dependencies.

I will provide some examples of ongoing efforts by other actors in the field for objective on how these interdependencies manifest themselves to make them more clear. Finally, I will go over the Navigating the Quantum Divide(s) (Gercek & Seskir, 2025) study as an example on how the identification of these critical conditions and path-dependencies can inform and guide management and policy making decisions by the relevant actors in the field.

3.1 Highlighted Points from Previous Chapters and Interconnections

In this section, I will go over the points highlighted in the previous two chapters. A reformulated summary of points highlighted in Chapter 1 per landscaping domain is provided below:

Commercial Landscape

1. The US emerges as the clear leader among nations if the object of analysis is limited to countries, but there is still ongoing competition among regions within the Global North.
2. A pronounced gap exists between the Global North and Global South in terms of development of quantum technologies.
3. The US is identified as the initial primary market for quantum computing applications.
4. Unlike A.I., quantum technologies are subject to regular market forces.

Academic Landscape

1. Over the past 25 years, quantum technologies have demonstrated a steady increase in scholarly publications, contrasting with other fields like A.I. (which is in exponential growth period) and nanotechnology (which has a saturated and even declining publication curve).
2. China has established a strong presence in academic publications, supported by a very highly centralized funding approach that distinguishes it from other regions.
3. A relative lack of co-funding activities between major funding agencies across regions reflects limited global collaboration in the field.

Technical Landscape

1. Research on quantum technologies is highly diverse, encompassing multiple physical approaches at varying QTRLs, with no clear dominant approach yet.
2. While the cloud-based quantum computing model has been a dominant assumption since 2016, recent years have seen a resurgence of interest in on-premise quantum computing, with no clear winner between operating models or actors.
3. Quantum technologies as an umbrella term encapsulate multiple trends, each unique to different subdomains, rather than following a unified technical trajectory.

Education and Outreach Landscape

1. There is a clear upward trend in education and outreach activities related to quantum technologies.
2. A new discipline-specific culture is forming around quantum technologies, reflecting the growing maturity of the field.
3. Public perception, professional expectations, and the role of hype play a critical role in shaping the evolution of quantum technologies.

Geopolitical Landscape

1. Rising geopolitical tensions are likely to elevate the importance of debates on open versus closed-border collaborations.
2. In the near term, quantum technologies are unlikely to have direct relevance to military conflicts.
3. The uncertainty around dominant physical hardware modalities has a cascading effect on other layers of the technology ecosystem, intertwining geopolitical considerations with technical development.
4. Approaches to securing sensitive communications against quantum threats (via QKD or PQC) vary significantly across regions, potentially leading to further technical fragmentation.

Similarly, for Chapter 2, the highlighted points related to responsible quantum technologies activities were the following:

1. **Emerging Interest:** Responsible QT is a nascent field that has gained traction in recent years. While there is potential for rapid growth, its future trajectory remains uncertain.

2. **Institutionalization of Efforts:** There is a noticeable increase in institutional support for responsible QT, reflected in the establishment of dedicated centers, labs, and the organization of recurring events focused on this domain.

3. **Community-Driven Initiatives:** Beyond traditional education and outreach, the quantum community has shown significant self-organization on socially relevant topics, including hype management, gender equality, EDI, and sustainability.

There are also some critical perspectives on responsible QT efforts which have raised the following concerns:

1. **Risk of Premature Constraints:** Imposing ethical constraints at this early stage of development may hinder technological progress and compromise potential benefits.

2. **Sufficiency of Existing Frameworks:** Existing technology governance frameworks may already provide adequate guidance for quantum technologies, rendering additional measures unnecessary.

3. **Lack of Practical Measures:** The principles and values proposed in responsible QT efforts often lack actionable and viable steps that can be integrated into technology development practices.

Building upon these, I will present four connections that can be presented as critical opportunities for responsible QT efforts to address. The connections made here rely on contextual understanding and extrapolation of highlighted points from the previous chapters, hence there can be a host of different interdependencies derived by linking the provided insights and exploring their potential implications. The four I want to emphasize are below:

Connecting Technical Landscape with Community-Driven Initiatives: The diversity in research approaches and lack of a dominant technical trajectory in quantum technologies provide an opportunity for community-driven initiatives to shape socially relevant issues. For example, the quantum community's self-organization around technically highly relevant topics like sustainability can guide development paths, particularly as no single technical approach yet dominates the field.

Linking Education and Outreach with Critical Perspectives on Responsible QT: The upward trend in quantum education and outreach highlights the growing public and professional engagement with the field. However, the critique that responsible QT efforts often lack actionable measures suggests a gap in these efforts' ability to translate awareness and values into concrete development practices, an issue that outreach programs and communities could potentially address.

Integrating Geopolitical Landscaping with Risk of Premature Constraints and Narratives: The geopolitical fragmentation in quantum technologies, especially concerning sensitive communications and hardware modalities, underscores as one of the challenges of implementing global responsibility measures. Critics' concerns about premature ethical constraints resonate with this fragmentation, suggesting that responsible QT efforts must carefully navigate regional differences without proposal that will be perceived as stifling innovation. This could be addressed by developing region-specific guidelines that account for geopolitical realities while fostering a minimum standard of global coherence. Furthermore, responsible QT efforts could play a critical role in shaping public perceptions, using carefully crafted narratives to minimize the risks of accelerated fragmentation and promote international collaboration.

Technical Landscape and Sufficiency of Existing Frameworks: The diverse technical approaches in quantum technologies, with no clear dominant modality, highlight the need for adaptable governance. Critics' arguments that existing frameworks may suffice resonate with the technical landscape's variability, suggesting that rather than creating entirely new structures, initial efforts should focus on understanding and tailoring existing frameworks to quantum-specific contexts. This requires the involvement of expertise and communities that goes beyond quantum technologies, requiring truly interdisciplinary collaboration between experts from both different technology domains and different scientific domains, involving technical, legal, and social field experts.

These are some connections that can be, and to a certain extent are being, established regarding a more responsible future for quantum technologies. Below, I will provide some examples from the field on each of these connections.

Connecting Technical Landscape with Community-Driven Initiatives: Two examples of this can be presented as the Quantum Energy Initiative (first introduced in Section 2.2) and OpenQuantum[57], a UK-based initiative to develop open-source resources for quantum computing hardware. The QEI both consists of and promotes[58] the researchers active in doing technical investigations of energy and resource constraints on quantum technologies (primarily quantum computing). From a value-sensitive design perspective (Umbrello, et al., 2024) this is a core activity and requirement for sustainability considerations. The reason I believe they are a great example is that, during the formation period of QEI, none of the researchers involved knew about value-sensitive design or even technology assessment, they tried to reinvent the wheel from scratch by trying to calculate the energy cost of screws in their systems and such. In time, and via interacting with experts that operate beyond the QT field, they developed into a truly admirable honest broker of technical knowledge. Companies that wouldn't normally share their device specifications in terms of energy consumption can now do it via QEI.

[57] https://openquantumdesign.org/ (Accessed 23 May 2025)
[58] https://quantum-energy-initiative.org/category/videos/ (Accessed 23 May 2025)

My second example, OpenQuantum, is a newer one that was formed in 2023. The reason I put them as an example to this item is a concern raised in our Responsible Quantum Technologies workshop in Singapore (see Table A1.3) by a representative from the Malaysia Quantum Information Initiative (MyQI)[59] when discussing open-source. He highlighted the fact that all open-source projects and initiatives in the domain of quantum computing rely on hardware in the end. And if the hardware that they rely on is proprietary (which is the case for almost all), it reduces the value of autonomy gained from these open-source projects. In the model OpenQuantum operates under, it is not just the software that is open-source, but also the hardware. There are still of course many IP considerations and it is not an easy task to develop a truly open-source hardware approach given the sheer amount of active patents by industry and academic players around the globe (Seskir & Willoughby, 2023), yet there are efforts in this direction. A historical example of this approach is Tim Berners-Lee not patenting his invention and pushing for standards that rely on royalty-free technology via World Wide Web Consortium[60], leading to the rapid adoption of the internet.

Linking Education and Outreach with Critical Perspectives on Responsible QT: A clear example of an attempt to create such a link was our Strengthening and Entangling Global Quantum Roots (SeGQuRo) project, which was a joint effort led by KIT (ITAS) and TU Delft (EEMCS), and primarily funded by the CQS in the NL[61]. The aim was to strengthen the grassroots communities in quantum technologies around the globe, especially those in countries without strong national support or available resources for communities active in quantum technologies, mostly targeting the existing communities in the Global South and Widening countries. The project was conducted between February-September 2024, consisting of six online meetings, and a one week long in-person event in the Netherlands, primarily at Delft with a one day excursion to Amsterdam (see Table A1.3). The in-person event hosted representatives of local grassroots communities from Argentina, Brazil, Bulgaria, Colombia, Germany, Greece, Lithuania, Poland, Romania, Serbia, Singapore, Tunisia and Turkey, while those representatives from Ghana, Libya, Nigeria, Pakistan, Philippines, and Zimbabwe joined online to the hybrid sessions. The event covered topics on ELSA of QT and a one full day workshop on EDI. In addition to ELSA and EDI content, the event also consisted of lab visits to QuTech, House of Quantum in Delft, the Quantum Application Lab at CWI, and the Quantum.Amsterdam Experience (see Appendix A2 for the full program - the names of the speakers are removed).

The feedback from participants of the on-site event was revealing of the value of such a linking. On the feedback form, one participant wrote "*I never thought that the legal issues regarding this technology were so important*." Another wrote "*Would have greatly liked another day (probably at start) about politics - felt like that underpinned most conversations we were having*." Overall, the feedback was extremely positive and there were several follow-up events organized by participants focusing on topics ranging from EDI to security, regional ecosystem building to impact of geopolitics. There are already plans to continue these activities in 2025 and beyond.

[59] https://www.myqi.my/ (Accessed 23 May 2025)
[60] https://www.w3.org/ (Accessed 23 May 2025)
[61] https://quantumdelta.nl/news/six-projects-funded-by-open-call-from-the-centre-for-quantum-and-society (Accessed 23 May 2025)

Integrating Geopolitical Landscaping with Risk of Premature Constraints and Narratives: Some core publications of this thesis work, the ones on democratization of QT (Seskir, et al., 2023a) and pitfalls for defence and security by narratives on QT (Seskir, et al., 2024a) are addressing this point. The geopolitical competition concerns raised in Section 2.3 by critics of responsible QT efforts rely on the narrative of *QT as an arena for geopolitics* (Seskir, et al., 2023a, p.9), which also partially emanate from the narrative of *Quantum computing as a threat* (p.11). These narratives also support the introduction of exclusionary mechanisms to the participatory efforts and create time pressure on the potential deliberation process and prioritizes security-oriented stakeholders' needs over others.

Two good approaches in countering this encroachment of geopolitical and security priorities over other responsible QT efforts are demanding a minimum standard of global coherence and shifting the focus from military and defence applications to civilian applications with both local and global relevance. In the first regard, efforts from organizations like OECD[62], UNESCO (2024), WEF (Coates, et al., 2022), and others are welcomed by many. These efforts try to push for the groundwork on which the minimum standard of global coherence can be constructed upon. Similarly, there are more specialized efforts from globally recognized organizations active in the security and defence domain such as UNIDIR[63] and Stockholm International Peace Research Institute (SIPRI)[64] that aim at this goal.

In terms of shifting the focus to more civilian applications, initiatives such as the $5M XPrize Quantum Applications Award for SDG relevant quantum computing applications, Deloitte's Quantum Climate Challenge[65], the Airbus and BMW Quantum Computing Challenge[66], NYUAD International Hackathon for Social Good on Quantum Computing and SDGs[67], Earth observation efforts at the European Space Agency (ESA) utilizing quantum sensors (Strangfeld, 2023), formation of the Open Quantum Institute (OQI) focusing on SDG-relevant applications of quantum computing[68], and their collaboration[69] with the UNICEF-ITU joint initiative Giga[70] on how QT can help close the digital divide in education and connectivity are just a few examples. There is a strong momentum in the community towards developing and promoting civilian applications of quantum technologies, supported both by a range of commercial and civil society stakeholders. It aims and helps with countering the narrative that military and defence

[62] https://www.oecd-events.org/global-forum-technology (Accessed 23 May 2025)
[63] https://unidir.org/event/2024-innovation-dialogue-quantum-technologies-and-their-implications-for-international-peace-and-security/ (Accessed 23 May 2025)
[64] https://www.sipri.org/news/2024/sipri-researchers-lead-discussions-quantum-technologies (Accessed 23 May 2025)
[65] https://www.deloitte.com/de/de/issues/sustainability-climate/deloitte-quantum-climate-challenge.html (Accessed 23 May 2025)
[66] https://www.airbus.com/en/innovation/digital-transformation/quantum-technologies/airbus-and-bmw-quantum-computing-challenge (Accessed 23 May 2025)
[67] https://sites.nyuad.nyu.edu/hackathon/ (Accessed 23 May 2025)
[68] https://open-quantum-institute.cern/ (Accessed 23 May 2025)
[69] https://indico.cern.ch/event/1461128/timetable/ (Accessed 23 May 2025)
[70] https://giga.global/ (Accessed 23 May 2025)

applications are the primary reason why quantum technologies are being supported by so many countries around the globe (see Figure **C1.1.1**), shifting the focus from defence to commerce.

Technical Landscape and Sufficiency of Existing Frameworks: One good example of this is the preliminary work conducted by Elija Perrier on quantum fair machine learning (2021). As briefly mentioned in Section 2.3. For quantum machine learning models the regular tool set developed for classical machine learning models is not directly applicable and requires considerable additional technical research and effort. The current technical framework might not even be applicable to quantum machine learning and needs to be tailored to fit that purpose.

Two leading academic research groups that are generating knowledge and publications from a legal and regulatory perspective are the 'Law and Governance of Quantum Technologies' Research Group[71] at UvA led by Joris van Hoboken under the Action Line 4 efforts of the QDNL, and the Stanford RQT[72] under SLS led by Mauritz Kop. There are also highly valuable contributions to this topic from a more ethics-oriented angle out of TU Delft in the Netherlands[73], IQEL in Austria[74] and the Oxford RTI in the UK[75].

In the European context, this would practically mean the explicit exploration of compliance of quantum technologies related development and products to regulatory frameworks such data protection (GDPR), climate efforts (e.g. CBAM & CSRD), digital (e.g. DMA & DSA), and the dual-use export controls. Different realizations of the quantum internet might have divergent fits to the legal bases of GDPR, DMA, or DSA. Implementation of applications such as blind quantum computation (Wei, et al., 2024) might not have direct coverage under these regulations, hence might require amendments to them.

3.2 Identification of Critical Conditions for Responsible Quantum Futures: Navigating the Quantum Divide(s) as a Case

Building upon some of the findings of Chapter 1 and partially on Chapter 2, we initiated a study on investigating the concept of emerging quantum divides (Ten Holter, et al., 2022) and how to navigate them, with a co-author who was a KIT Aspiring Grant (Doc) recipient visiting ITAS for four weeks in October 2023. These efforts led to the manuscript titled Navigating the Quantum Divide(s) (Gercek & Seskir, 2025), focusing on the potential quantum divides that may emerge for different communities and contexts, and suggestions on how to navigate them to minimize their negative impact. We focused on multidirectional impacts that quantum technologies might have on science, technology, geopolitics, and societal structures. Out of that study, I will cover one critical condition for each aspect.

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[71] https://www.ivir.nl/projects/law-and-governance-of-quantum-technologies-research-group/ (Accessed 23 May 2025)
[72] https://law.stanford.edu/press/sls-launches-a-first-of-its-kind-center-for-responsible-quantum-technology (Accessed 23 May 2025)
[73] https://www.tudelft.nl/en/tpm/research/tpm-labs/quantum-governance-and-values-lab/ethics-of-quantum-technologies (Accessed 23 May 2025)
[74] https://www.uibk.ac.at/projects/iqel/index.html.en (Accessed 23 May 2025)
[75] https://www.rti.ox.ac.uk/ (Accessed 23 May 2025)

First, we argued that the "Quantum Divide in Science" represents a critical challenge as quantum technologies advance. While these technologies hold transformative potential for science, enabling novel tools and methods, their benefits are not likely to be distributed equally. Access to advanced quantum tools remains concentrated in well-funded institutions, creating significant barriers for others to participate. At the same time, the adoption of these technologies is uneven across disciplines, leaving some research areas lagging behind and amplifying existing disparities in scientific capability. These inequities risk shaping who can contribute to and influence the development of quantum technologies, potentially entrenching power and expertise in specific regions or fields. To address these challenges, we propose to prioritize collaboration and inclusivity.

One example we focused on was life sciences, more specifically biology and medical applications. The recent progress in developing magnetoencephalography with optically pumped magnetometers (OPM-MEG) is highly praised as a promising tool for the next generation of functional neuroimaging (Brooks, et al., 2022; Alem, et al., 2023). Current MEG devices require considerable physical infrastructure like cryogenics and superconducting devices, they are similar to MRI devices in their physical appearances. In comparison, the novel OPM-MEG devices are the size of a bike helmet, a helmet especially 3-D printed for the subject's head with dozens of synchronized quantum sensors placed on it. Enabling the utilization of portable and wearable quantum sensors that can perform MEG operation to enhance the opportunity space for questions that can be asked by neuroscientists using these tools for data gathering from subjects in motion.

In terms of biology, for instance, Aiello (2023) complains that quantum biology is not being regarded as a "legitimate" scientific field, although it carries significant potential in many areas. According to Aiello, the reasons for this are the absence of a cohesive quantum biology community, lack of experimental verification, and the continued presence of scientific silos at institutions (p.2). This resonates with a recent funding programme announced by VW Stiftung in Germany[76] aiming "*...to support the proof of quantum effects in biological systems, thereby increasing the acceptance of this research field*". Similar arguments can be applied to the lack of adoption of quantum chemistry techniques using quantum computers for full model simulations by chemists who are sticking with widely available density-functional theory modelling, even though quantum computers hold great potential for the field (Cao et al., 2019).

To mitigate the impact of such a divide emerging in sciences, we stress upon the importance of building shared research infrastructures and fostering interdisciplinary initiatives to broaden access to quantum technologies and encourage their integration across diverse fields. Creating targeted funding programs that support the use of quantum technologies for various scientific challenges in different fields (such as the VW one) can help democratize its benefits and avoid their concentration in a few hands or a few disciplines. By navigating these, it can be ensured that the transformative potential of quantum technologies supports equitable progress and enriches the global scientific community as widely as possible.

[76] https://www.volkswagenstiftung.de/en/funding/funding-offer/next-quantum-biology (Accessed 23 May 2025)

As our second point, we targeted the potential quantum divide that may emerge between ecosystem actors (especially in different regions) that focused on divergent technologies and hardware modalities to realize quantum systems (see the discussion in section 1.3). The development of quantum technologies is shaped by technology path-dependencies, which pose a critical challenge for ensuring equitable outcomes for a responsible future. Early choices in the design and adoption of these systems can lock ecosystems into specific trajectories, favoring certain modalities or approaches—such as superconducting qubits or trapped ions—while sidelining others. This dynamic risks the entrenching of inefficiencies and limits innovation by prioritizing short-term gains over a broader exploration of possibilities. The resulting "lock-in" could create divides, not only between countries and organizations with different resources but also among innovation ecosystems, as some actors align with dominant approaches while others are left behind. The National Academies of Sciences, Engineering, and Medicine report titled "Quantum Computing: Progress and Prospects" (2019) provides a clear example of this. It emphasizes the concept of a virtuous cycle within the semiconductor industry related to transistors. In this cycle, the adoption of new technology in products leads the industry to make more money, which is then reinvested in the development of newer technology. This is likely to occur in the quantum domain as well.

To navigate these path-dependencies, a promotion of diverse and adaptable the development and adoption of these technologies is advised. Encouraging investments across multiple technological approaches can mitigate the risks of premature lock-in, ensuring that alternative solutions remain viable. Slowing the pace of commercialization to allow for deeper exploration of technological possibilities can also prevent suboptimal outcomes and reduce barriers for new entrants. By fostering a more open and flexible innovation ecosystem, quantum technologies can evolve in a way that maximizes its potential benefits while minimizing exclusion and inefficiencies along the way.

The third point we focused on is the “Quantum Divide between Countries” which is to a certain extent the most explored one in the literature. We argued that the development of quantum technologies is creating new divides between countries, driven by disparities in resources, infrastructure, and strategic priorities. Wealthier nations with established technological and industrial bases are better positioned to invest in these technologies, enabling them to shape its development and secure early advantages. Meanwhile, smaller or less-resourced nations risk falling further behind, particularly as global competition intensifies. These divides are compounded by protectionist policies (Ten Holter et al., 2022) and geopolitical tensions, which prioritize national self-sufficiency over international collaboration (Shelley-Egan & Vermaas, 2024). As a result, quantum technologies could deepen global inequalities, concentrating its benefits in a few leading countries while limiting access and opportunities elsewhere. To address this challenge, greater international collaboration and strategic inclusivity needs to be fostered. Regional partnerships, such as those within the European Union, can pool resources and expertise, creating opportunities for smaller nations to participate meaningfully in the quantum technologies landscape (see Figure **C1.3.4** for EuroQCI as an example). Supporting high-risk, high-reward projects in emerging economies can also enable these nations to carve out unique niches, reducing reliance on dominant players (Xuereb, 2022), but this is a high-risk option as betting on a hardware modality that would not become the dominant one might lead to

considerable opportunity costs. By emphasizing shared values, equitable resource allocation, and collaborative innovation, the risks of a growing quantum divide between countries can be mitigated, and the benefits of quantum technologies can contribute to global progress, such as addressing SDGs (Converso, et al., 2024), rather than exacerbating existing inequalities.

Finally, we covered the “Quantum Divide within Societies.” The argument we proposed was that the rise of quantum technologies risks exacerbating divides within societies, deepening existing inequalities in access to technology, education, and economic opportunities. As applications of quantum technologies emerge, such as quantum computing, sensing, and communication, their benefits will likely first reach those with the resources, infrastructure, and skills to leverage them. This uneven access could translate into social and economic disparities deepening, leaving marginalized communities further behind. Additionally, the advanced expertise required to develop and use these technologies could create a skills gap, limiting participation to a small, highly specialized group while excluding broader segments of society (Meyer, et al., 2024). Addressing this divide requires proactive measures to democratize access to these technologies (Seskir, et al., 2023a) and its opportunities. Expanding quantum education and training programs, particularly in underserved regions and communities, can build a more inclusive workforce and ensure broader participation. Investing in public infrastructure and creating accessible platforms for quantum applications can help bridge gaps in access and enable diverse groups to benefit from quantum advancements. By prioritizing inclusivity and equity in the development and deployment of quantum technologies, they can become a source of division and instead contribute to societal progress as a whole.

Every aspect of quantum divides we covered in this article can lead to practical policy recommendations. For example, building shared research infrastructures and fostering interdisciplinary initiatives to broaden access to quantum technologies and encourage their integration across diverse fields can mitigate the negative impact of a divide emerging in the scientific community. Measures such as VW Stiftung’s NEXT-Quantum Biology funding programme are good examples. Allowing room for deeper exploration of technological possibilities in the physical realization of quantum technologies can help with mitigating the impact of betting on the wrong modality and might spread the financial and opportunity costs. Focusing on utilizing quantum technologies to address global problems rather than regional or local power play can help narrow the divide between countries. And expanding education and access opportunities to marginalized communities within societies can locate quantum technologies not as a factor in widening the societal gaps but as a one that helps narrow them.

Table **C3.2.1**: Publication contributions to the topics covered in Chapter 3

Title / In-text citation	**Journal Publication**
Navigating the Quantum Divides (Gercek & Seskir, 2025)	Published in *IEEE Engineering Management Review*

There are other issues that we haven’t covered in the article yet that are relevant for the topic, such as the growing multi-bilateralism approach, especially on how the US and China approach regional alliances such as the EU and ASEAN. Instead of addressing them as a unit, these

geopolitical powers prioritize bilateral relations with member states, giving themselves better leverage in such negotiations. Another important topic that we haven't covered is the dynamics of convergence between emerging technologies, such as A.I., synthetic biology, and new space. The future of quantum technologies is not an isolated manner, even on the technical level. It is highly entangled with the future of other emerging technologies, which is rarely addressed.

3.3 Further Critical Conditions for Responsible Quantum Futures

As we are reaching the conclusion of this thesis work, I want to provide a list of further critical conditions that appeared during the course of this work but I was unable to produce publishable knowledge on. One of my research questions was:

- **RQ2:** What are the relevant topics and possible critical path dependencies for the development of these technologies responsibly?

Below, I provide a rough list of items that are relevant and might lead to possible critical path dependencies in the development trajectories of these technologies responsibly. The first four categories (technology, ethical, legal, social) are more topic oriented, and the fifth titled critical is a combination from the former four.

Technology topics: Which modality for quantum computers and for quantum networks?
- Cloud or on-premise (quantum centric HPC vs. quantum personal computers)
- Energy consumption
- Supply chains and sovereignty
- Raw materials (not discussed extensively in the literature)
- Convergence with other technologies (like A.I.)

Ethical topics: Going fast or going wide, how inclusive should quantum technologies be?
- Within Europe
- The Global South
- Widening inequalities vs. getting a strategic advantage

Legal topics: How fenced off will the tech be between and within countries?
- Export controls (different types), knowledge security
- Will citizens ever become users of quantum technologies in the near term?
- How critical really are quantum technologies for defense?
- Responsibilities of the states (crypto-threat, ensuring human rights, national security)

Social topics: Hype, narrative, ownership
- Hyping, expectation management, quantum winter, ambitions vs. false promises
- Cultural perception and discourse (normalization vs. mystification of quantum tech)
- Ownership of the tech (is it physicists or no longer physicists)
- EDI, gender, and other empowerment efforts

Critical path dependencies:

- Winning modality and its supply chain (global or local / energy-efficiency embedded?)
- Balance between hype and promises / expectation management / and direction
- Cultural perception and discourse (normalization vs. mystification of quantum tech)
- How the quantum divide(s) are navigated
- Formation of QIST as a new research field (happened for A.I. didn't happen for nano)
- Successful convergence or not

Conclusion & Discussion

As described in the introduction to Chapter 3, the findings of this thesis as a whole can serve as valuable inputs for practices such as scenario planning, strategic foresight exercises, and the design of CTA or transformative vision assessment workshops for quantum technologies. Rather than offering definitive answers to what a responsible quantum future entails or how it can be achieved, this thesis represents a comprehensive exploratory effort, with some examples to provide guidance. Its focus is on uncovering how responsible quantum futures can be conceptualized and identifying the critical conditions and path-dependencies that shape the responsible development of these technologies.

To achieve its goal, the thesis work (and the resulting manuscript) focused on two distinct categories of efforts. First is the landscaping part, covered in Chapter 1. It provides a comprehensive picture of where quantum technologies is as a whole in terms of its commercial, academic, technical, educational, and geopolitical states. Second is the conceptual and exploratory efforts, which are covered in Chapters 2 and 3 via the introduction of responsible quantum technologies as an evolving topic, and the identification of associated critical conditions and path-dependencies in this context. All these efforts led to two main sets of outcomes. First one is the list of highlighted points covered in section 3.1, which are outcomes distilled from the investigation of different landscapes in Chapter 1 with the responsible quantum technologies lens introduced in Chapter 2. Second, the critical conditions identified in sections 3.2 and 3.3, which are relevant topics of further study in the area of responsible QT.

Although I have dabbled in it briefly (Çevik & Seskir, 2023), I am not a strong believer of the many-worlds interpretation of quantum mechanics, but I am also not a determinist or a superdeterminist. I believe in free will and human choice, and that our collective actions have the potential to alter the course of history and "natural" evolution of superstructures. Yet, I also know that collective directed action requires a collective will towards a shared vision (and sometimes against an expected yet undesirable one). My hope is that this thesis work can contribute to informing those actors in the domain of quantum technologies to have a self-reflexive moment on what kind of futures they desire (or fear), and what are the critical conditions that lead us to the path towards (or against) those futures. As I stressed upon previously, this thesis does not provide a set of definitive answers on what those conditions are, but a list of potential options that rely on a comprehensive analysis of the current landscape and the theoretical lenses that are developed to address the control-promote dilemma in tech governance. Different formulations, especially more critical ones weighing on the control side, are entirely possible, but also out of scope of this work.

The second primary outcome of this thesis work is what these developments in QT tells us as TA and STS researchers on the state of emerging technologies in relation to ELSA topics. In that regard, I have developed four argumentation lines on what we (as TA and STS researchers) can learn from investigating QT further:

1. Quantum Technologies is not artificial intelligence, neither is it nanotechnology, nor nuclear. Although there are many similarities and some patterns between how these technologies evolve (useful for both innovation studies and ELSA of emerging technologies), there are very clear differences. Nano debates of the early 2000s or the recent A.I. debates (especially after the release of ChatGPT) are both quantitatively and qualitatively different from debates in the field of QT. The historical and geographical conditions these technologies develop create unique features or shape some common features in unique ways. The fact that IBM made their five qubit device publicly and freely accessible in 2016 (six years before OpenAI did the same for ChatGPT) caused a proliferation of grassroots organizations at a much earlier point in technology development compared to other emerging technologies. This, in return, kickstarted discussions on a potential 'quantum divide' (Ten Holter, et al., 2022; Gercek & Seskir, 2025) at a stage when the technology is still (for all practical purposes) useless for anything other than research. In comparison, discussions on the digital divide only emerged in the late-90s (years after the internet was an established infrastructure in many developed countries) and on the A.I. divide in early 2020s (when the technology was already being actively deployed). This shows us that it is possible for researchers and grassroots organizations (i.e. civil society actors) in emerging technologies fields to react to visions of unequal access in the future in very early stages of technology development as well. Visions carry weight and mobilization for social action against unequal outcomes is possible even before those outcomes are realized in the world, even when the topic is something as obscure for a majority of the population as quantum technologies.

2. The usual TA and STS narratives on emerging technologies, especially in the European-context, revolve around safeguarding the public from the harms of these technologies, mostly caused by the private industry actors for profit maximization, especially for situations where gains are privatized while harms are socialized. This results in most action recommendations to fall under the category for further regulation of private actors through public and legal means. Yet investigation of QT shows that this does not necessarily apply in QT. Even though unfair privatization of gains by certain industry actors are seen as problematic by some (Arrow & Marsh, 2023), the more common narrative in the field is that premature export controls and implementation of knowledge security regimes (Sparkes, 2024; Titcomb, 2024; Zhang, 2024) are actually counterproductive towards both scientific collaboration and democratization of these technologies. It is more likely to find civil society actors siding with large multinational technology development companies against the type of government regulation they see as excessive, compared to the usual state where civil society actors demand more regulatory action against these companies. Again, this seems to be related to the

technology being in earlier stages of its development cycle, without any near-term harm to society. Furthermore, even the envisioned harms (threat to public-key cryptography via quantum computers or novel surveillance techniques using quantum sensors) that can be caused by quantum technologies are usually attributed to not private by state actors. Additionally, plans of enabling secure and private communication for governmental actors (e.g. EuroQCI) while denying the public of such privileges (see Chatkontrolle debates (Breyer, 2024)) shifts the debate from “gains are privatized while harms are socialized” to something more in the line of “gains are nationalized while harms are socialized.” The closest example in the literature might be nuclear power (Jasanoff & Kim, 2009), yet with the clear difference that it wasn’t the state which spearheaded the development of quantum computers but private companies (such as IBM, Google, and Microsoft). This is a relatively uncharted territory for TA and STS, and further investigation of how the situation and the debates around it evolve in QT might provide useful insights into this emerging shift in dynamics of responsible development.

3. Changing narratives and focus in the QT field in recent years is very apparent. As described in the Prologue and section 1.5 (The Geopolitical Landscape of Quantum Technologies), the debates around QT are becoming increasingly securitized. Introduction of export controls (and discussions on arms controls), development of knowledge security regimes that practically bars hiring of students from certain nationalities, introduction of both inward and outward investment screening mechanisms, and many other actions are taken towards creating a more securitized QT ecosystem. There is pushback against this both from multinational industry and civil society actors, while there is some support from national industry actors (especially by those that directly benefit from these interventions). There are many exogenous reasons that have very little to do with the development trajectory of QT. The Russian invasion of Ukraine, increasing geopolitical tensions between China and the US, and growing instability in many different regions, when combined with the heightened vigilance caused by the public display of capabilities of LLMs expectedly caused a major shift in narrative from focusing entirely on economic and prosperity reasons to support the development of QT to more security-oriented ones. Yet there are endogenous reasons for this as well, as it is repeatedly stated during this study in different venues by a variety of actors that the development pace of QT (especially quantum computers) actually surpassed the expectations and timeline for a cryptographically relevant quantum computer is now pushed backwards to the end of 2030s (BSI, 2024). It is unclear how this dynamic will play out within the QT ecosystem. On the one hand, there are some who think that when a community summons the “defence genie” for funding or prestige, it is hard to put the genie back in the bottle before a wave of failures and disillusionment hits the ecosystem. On the other hand, the potential danger posed (or, depending on which perspective you assume, the advantage presented) by the introduction of cryptographically relevant quantum computers to state arsenals for cyberwarfare is too high to ignore. There are also legal obligations by states and companies to prepare for the potential risks caused by the advent of such quantum computers. Therefore, this is a highly relevant dynamic to study from a TA and STS angle and engage with from a deliberative democratic angle.

4. Finally, studying how the diplomacy and foreign relations worlds are interacting with QT can yield fruitful insights on how technology (especially EDTs) influence these and gets influenced by them. The concept of Techplomacy[77] or Tech Diplomacy[78] is a somewhat recent one, gaining traction following Denmark's adoption of this approach and appointment of the first "tech diplomat" to Silicon Valley by Denmark in 2017. This has already caught on in QT. For example, the Austrian BMEIA is organizing tech diplomacy events on QT[79], and that Denmark will host the EQTC this year[80] (Nov. 2025) with direct contributions from their International Quantum Hub under the Department for Techplomacy in the Ministry of Foreign Affairs. It might be particularly interesting to investigate these relations from a TA perspective as currently when QT development is being discussed and funded, the relevant governmental agencies are overwhelmingly science & research organizations (like the NSF in the US, EPSRC in the UK, BMBF in Germany). This creates a situation where strategic and funding decisions are being taken following the priorities of science-oriented organizations, which sometimes yield contradictory actions where countries sign Memorandums of Understanding to promote collaboration in QT development, while implementing export controls and investment screening against each other. An overarching strategy in this regard is especially called for in the EU, which resulted in the decision to come up with a Quantum Strategy through a Quantum Act, the details of which are still in flux while this thesis work is being finalized[81]. Involvement of foreign ministries (and priorities emanating from foreign affairs) for decisions on technology is something being growingly demanded within the QT ecosystem, especially regarding discussions on technology sovereignty and supply chain dependence/resilience for critical infrastructure (which also covers the digital infrastructure). Therefore, using QT as a case study to study how Tech Diplomacy systems operate can be pursued, and investigating and supporting how the wider responsible QT efforts are taking into account and balancing a growing number of interests and priorities is a novel challenge for TA researchers, one that can be highly useful for preparing the field for future EDTs.

Combining these four, I argue that investigating QT through the lens of TA and STS not only highlights unique patterns of societal engagement and governance distinct from other emerging technologies like A.I. or nanotechnology but also brings forth new conceptual and practical challenges to tackle. Unlike conventional narratives in our fields focused primarily on curbing privatized gains and socialized harms, QT introduces scenarios where governmental interventions, often securitized in nature, may inadvertently create conditions that nationalize benefits while distributing risks to society. These emerging dynamics require TA researchers and policymakers to rethink conventional wisdom about regulation, governance, and

[77] https://techamb.um.dk/the-techplomacy-approach (Accessed 23 May 2025)
[78] https://www.weforum.org/stories/2023/02/what-is-tech-diplomacy-experts-explain/ (Accessed 23 May 2025)
[79] https://www.uibk.ac.at/en/disc/events/techdiplomacytalk/ (Accessed 23 May 2025)
[80] https://www.eqtc.eu/ (Accessed 23 May 2025)
[81] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14675-Quantum-Strategy-of-the-EU_en (Accessed 23 May 2025)

public-private-civil society relationships in technology development. Furthermore, QT provides a fertile ground for studying how geopolitical tensions and diplomacy intersect with scientific innovation, especially given the growing emphasis on Tech Diplomacy and the increasing importance of technology as a highly relevant point of argument and contestation in great power dynamics. The interplay of security concerns, international cooperation, and the rapid, yet uncertain trajectory of QT highlights the need for a nuanced approach integrating diplomatic, strategic, and societal dimensions. Therefore, continued research into QT not only contributes directly to social shaping of technology and responsible governance frameworks specific to quantum innovations but also enriches broader understandings within TA and STS, preparing our fields to effectively manage and responsibly guide future EDTs.

Finally, when it comes to quantum technologies, it is an emerging set of technologies that rely on utilization of certain quantum properties, properties that are realities of our physical existence, which we have been aware of only since the last century. Even if they don't become a part of our technological toolset now, if the technological progress of humankind continues, they will be realized at some point. Wouldn't it be better if we can manage to use them for creating a better future instead of propagating our previous shortcomings?

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Appendix

Table A1.1: Events attended (title / organizer / date / location)

Event Title	Organizer	Date	Location
Inside Quantum Technology (IQT) The Hague 2022	3DR Holdings	21-23 Feb. 2022	The Hague, NL
Security in the Quantum Age	University of Jena	31 May 2022	Jena
Transatlantic Quantum Forum	TUM	16-17 Sep. 2022	Munich
Quantum and chips: Developing European industrial capabilities in quantum technologies	STOA	12 Oct. 2022	Brussels, BE
How will Quantum impact Business and Society?	Quantum Amsterdam	3 Nov. 2022	Amsterdam, NL
Launch of European Quantum Software Institute	PCQC	8 Nov. 2022	Paris, FR
Developing a governance framework for quantum computing	University of Amsterdam	20 Dec. 2022	Amsterdam, NL
Workshop on Ethical Implications of Quantum Communication	TU Delft	2-3 Feb. 2023	Delft, NL
DPG Spring Meeting of the Atomic, Molecular, Quantum Optics and Photonics Section	DPG	5-10 March 2023	Hannover
Launch of the Exploratory Quantum Technology Assessment Tool	Center for Quantum and Society	14 April 2023	Amsterdam, NL
INSQT Workshop On Current Missions And Component Developments	INSQT	22-23 May 2023	Jena
From Margins to Mainstream: Novel Perspectives on the Emergence of Fields and Markets	Aalto University	25-26 May 2023	Aalto, FI
Studio Quantum: Berlin	Goethe Institut	15 June 2023	Berlin
World of Quantum: 2nd International Trade Fair on Quantum Technology	Messe München	24-27 June 2023	Munich
20th International Conference on Quantum Physics and Logic	Institut Henri Poincaré	17-21 July 2023	Paris, FR

Table A1.1(cont.): Events attended (title / organizer / date / location)

Event Title	Organizer	Dates	Location
The Future of Quantum Technologies in Turkey and Around the Globe	METU Technology Policy Center	11 August 2023	Ankara, TR
INSQT Workshop on Space Quantum Internet	INSQT	30 Aug. - 01 Sep. 2023	Berlin
2nd Quantum Science and Engineering Education Conference (QSEEC23)	IEEE	17-18 Sep. 2023	Seattle, US
IEEE International Conference on Quantum Computing and Engineering - 2023	IEEE	17-22 Sep. 2023	Seattle, US
Quantum World Congress 2023	Connected DMV	26-28 Sep. 2023	Washington D.C. - US
IST-SET-198-RSY on Quantum Technology for Defence and Security	NATO STO	3-4 Oct. 2023	Amsterdam, NL
Workshop on the ethical and social implications of quantum sensing	TU Delft	5-6 Oct. 2023	Delft, NL
Quantum Effects: Exhibition and Conference for Quantum Technologies	Messe Stuttgart	10-11 Oct. 2023	Stuttgart
European Quantum Technologies Conference (EQTC) 2023	Quantum Flagship	16-20 Oct. 2023	Hannover
The Quantum Energy Initiative (QEI) Workshop 2023	QEI & CQT	20-24 Nov. 2023	Singapore, SG
Responsible Innovation in Defence and Security Conference	BENELUX & NATO ESCD	27 Nov. 2023	Brussels, BE
Quantum Innovation Summit	Vernewell Group	28-29 Feb. 2024	Dubai, UAE
Q2B Paris 2024	QC Ware	7-8 March 2024	Paris, FR
European Conference Quantum Technologies for Defence Current and future capabilities	ENDR, DG DEFIS	13-14 March 2024	Warsaw, PL
87th Annual Conference of the DPG and DPG Spring Meeting	DPG	17-22 March 2024	Berlin

Table A1.1(cont.): Events attended (title / organizer / date / location), all in 2024.

Event Title	Organizer	Dates (2024)	Location
Strategizing Quantum Science & Technology in the ASEAN Context	QTRic	25-26 April	Bangkok, TH
AFQC 2024: scale up!	DLR	13-14 May	Stuttgart
Quantum Climate Challenge Finals	Deloitte	22 May	Düsseldorf
Quantum & Society Research Colloquium	CQS, TU/e	31 May	Eindhoven, NL
Quantum Meets ‘24	QDNL	11-12 June	Amsterdam, NL
Recent Advances in Quantum Computing and Technology (ReAQCT)	ELTE, BME	19-20 June	Budapest, HU
Centre for Quantum and Society Program Day	CQS	27 June	Leiden, NL
Quantum World Congress 2024	Connected DMV	9-11 Sept.	Washington D.C. - US
3rd Quantum Science and Engineering Education Conference (QSEEC24)	IEEE	15-16 Sept.	Montreal, CA
IEEE International Conference on Quantum Computing and Engineering - 2024	IEEE	15-20 Sept.	Montreal, CA
Quantum Summit 2024	Bitkom	25-26 Sept.	Berlin
Geneva Science and Diplomacy Anticipation Summit 2024	GESDA	9-11 Oct.	Geneva, CH
Fertile Void: Quantum Paradoxes and the Physics of Living Matter	Goethe Institut / HKW	1-3 Nov..	Berlin
European Quantum Technologies Conference (EQTC) 2024	Quantum Flagship	18-20 Nov.	Lisbon, PT
Workshop on Exploring the Arms Control Implications of Quantum Technologies	QDNL / SIPRI	22nd Nov.	The Hague, NL

Tables **A1.1** and **A1.2** lists the events I attended during the doctoral studies and conducted participant observation, taking notes of the content and further details such as conversations, arrangements, an overview of apparent demographics (gender, race, etc.).

Table A1.2: Online Events attended (title / organizer / date)

Event Title	**Organizer**	**Date**
Quantum Eastern Europe: Creating Quantum Awareness in Eastern Europe (2022)	QURECA	5-6 May 2022
Quantum Science Days (QSD 2022)	QWorld	1-3 June 2022
Quantum Science and Engineering Education Conference (QSEEC) - *hybrid*	IEEE	18 Sep. 2022
Quantum Science Days (QSD 2023)	QWorld	29-31 May 2023
Building a National Innovation System for Quantum Technology - *hybrid*	University of Jena	7-8 Sep. 2023

Table **A1.3** lists the events I organized or co-organized with others during the period of my doctoral studies.

Table A1.3: Events (co-)organized (title / organizer / date / location)

Event Title	**Organizer**	**Date**	**Location**
Responsible Quantum Technologies 2021	ITAS	9 Dec. 2021	Online
Responsible Quantum Technologies 2022	ITAS	6-7 Dec. 2022	Karlsruhe
Ausstellung: Warum ist Quantenmechanik so wichtig beim Spielen? (part of Wissenschaftsreihe EFFEKTE)	Stadt Karlsruhe & ITAS	13-16 Dec. 2022	Karlsruhe
Responsible Quantum Technologies 2023	ITAS	27-28 July 2023	Karlsruhe
Grassroot Efforts in Quantum	Zeki & Lia	13 July 2023	Online
Grassroot Efforts in Quantum vol.2	Zeki & Lia	1 Dec. 2023	Online
Responsible Quantum Technologies 2024	ITAS	16-18 April 2024	Karlsruhe
Strengthening and Entangling Global Quantum Roots	TU Delft, ITAS	1-9 June 2024	Delft, NL
Responsible Quantum Technologies: Impact of Geopolitics in the Indo-Pacific Region	RSIS, SGInnovate, ITAS, CQT	15-16 Oct. 2024	Singapore, SG
Responsible Quantum Technologies 2025	ITAS, OECD	7-10 April 2025	Karlsruhe

A2. Strengthening and Entangling Global Quantum Roots Event Program

The Strengthening and Entangling Global Quantum Roots (SeGQuRo) project was a joint effort led by KIT (ITAS) and TU Delft (EEMCS), and primarily funded by the CQS in the NL[82]. The aim was to strengthen the grassroots communities in quantum technologies around the globe, especially those in countries without strong national support or available resources for communities active in quantum technologies, mostly targeting the existing communities in the Global South and Widening countries. The project was conducted between February-September 2024, consisting of six online meetings, and a one week long in-person event in the Netherlands, primarily at Delft with a one day excursion to Amsterdam (see the Program below). The in-person event hosted representatives of local grassroots communities from Argentina, Brazil, Bulgaria, Colombia, Germany, Greece, Lithuania, Poland, Romania, Serbia, Singapore, Tunisia and Turkey, while those representatives from Ghana, Libya, Nigeria, Pakistan, Philippines, and Zimbabwe joined online to the hybrid sessions. The event covered topics on ELSA of QT and a one full day workshop on EDI. In addition to ELSA and EDI content, the event also consisted of lab visits to QuTech, House of Quantum in Delft, the Quantum Application Lab at CWI, and the Quantum.Amsterdam Experience.

02.06.2024 – Sunday (Delft)

17:30-21:00 – Welcoming get-together

03.06.2024 – Monday (Delft-EEMCS)

09:00-10:00 – Introduction of the project SEGQuRo and the program

10:00-12:30 – Introduction of grassroots organisations by the participants (part one)

12:30-13:30 – Lunch break

13:30-17:00 – Introduction of grassroots organisations by the participants (part two)

04.06.2024 – Tuesday (Delft-EEMCS)

09:00-10:00 – Introduction of grassroots organisations by the participants (part three)

10:00-12:30 – Ethical Aspects of Quantum Technologies (QT)

12:30-13:30 – Lunch break

13:30-14:30 – Ethical Aspects of QT: Introduction

14:30-15:00 – Visualizing Quantum Reality in Quantum Technology

15:00-15:15 – Short break

15:15-16:15 – Roundtable discussion on the UNESCO process

16:15-17:30 – Social Aspect of QT: Presentation and discussion

[82] https://quantumdelta.nl/news/six-projects-funded-by-open-call-from-the-centre-for-quantum-and-society (Accessed 23 May 2025)

05.06.2024 – Wednesday Part 1 (Amsterdam-UvA/IViR)

10:00-13:30 – SEGQuRo Project - Amsterdam Workshop on Law and Governance of QT

10:00-10:20 – Welcome – Round of Introductions

10:20-11:00 – Access to Quantum Computing – Affordance of Infrastructure and Legal Thinking

11:00-11:10 – Short break

11:10-11:50 – Digital Sovereignty and Quantum Technologies

11:50-12:30 – Legal Instruments of (Q)Technological and Innovation 'Ringfencing'

12:30-13:30 – Lunch break

13:30-15:00 – moving to the Quantum Applications Lab (QAL)

15:00-15:45 – Introduction of QAL

15:45-17:30 – Tour of the Quantum.Amsterdam Experience

06.06.2024 – Thursday (Delft-EEMCS & X-TU Delft)

9:00 - 9:30 – Welcome and Ice-breaker session (exercise to warm up reflection and creativity: answering "who am I?" with a poem or drawings)

9:30 - 10:00 – "Women+ in Engineering Education" by IEEE WiE BeNeLux Chair

10:00 - 11:00 – "Neurodiversity and Intersectionality", TU Delft Education and Student Affairs

11:15 - 12:30 – "Reflective Dialogue Perspective Agility", TU Delft Reflective Engineering

12:30 - 13:45 – Lunch at TU Delft X

13:45 - 15:00 – "EDI from global to local to individual" by Policy Advisor at TU Delft D&I Office

15:00 - 16:30 – Camp Fire Talk Game

16:30 - 17:30 – Closing reflections (reflection on the day)

07.06.2024 – Friday (Delft)

09:30-10:30 – Visit to QuTech

11:00-12:30 – Visit to House of Quantum

12:30-13:30 – Lunch Break

13:30-15:00 – Case study of QWorld: The role of grassroots organisations in the QT ecosystem

15:15-16:00 – World Quantum Day (Online)

16:00-17:30 – Closing

A3. Search Query

The search query used for WoS searches on quantum technologies.

TS = (("quantum simulation" OR "quantum imaging" OR "quantum sensing" OR "quantum sensor" OR "quantum computation" OR "quantum computing" OR "quantum computer" OR "quantum coding" OR "quantum programming" OR "quantum error correction" OR "quantum error correcting" OR "quantum circuits" OR "quantum algorithm" OR "quantum algorithms" OR "quantum network" OR "quantum networks" OR "quantum channel" OR "quantum channels" OR "quantum cryptology" OR "quantum cryptography" OR "quantum key" OR "quantum teleportation" OR "quantum information" OR "quantum technology" OR "quantum technologies" OR “quantum gates" OR “quantum register" OR “quantum contextuality" OR “quantum decoherence" OR “quantum communication" OR “quantum memory" OR “quantum memories" OR “quantum repeaters" OR “quantum state transfer" OR “quantum zeno dynamics" OR “qubit" OR “qutrit" OR “qudit" OR “quantum correlations" OR “quantum entanglement" OR “quantum discord" OR “quantum noise engineering" OR “quantum state engineering" OR “quantum protocols" OR “quantum annealing” OR “quantum logic gate” OR “quantum internet” OR “quantum repeater” OR “quantum memory” OR “quantum photonics” OR “quantum photonic” OR “quantum biology” OR “quantum machine learning”) NOT (“qubit fluorometer”))

OR

TI = (("quantum simulation" OR "quantum imaging" OR "quantum sensing" OR "quantum sensor" OR "quantum computation" OR "quantum computing" OR "quantum computer" OR "quantum coding" OR "quantum programming" OR "quantum error correction" OR "quantum error correcting" OR "quantum circuits" OR "quantum algorithm" OR "quantum algorithms" OR "quantum network" OR "quantum networks" OR "quantum channel" OR "quantum channels" OR "quantum cryptology" OR "quantum cryptography" OR "quantum key" OR "quantum teleportation" OR "quantum information" OR "quantum technology" OR "quantum technologies" OR “quantum gates" OR “quantum register" OR “quantum contextuality" OR “quantum decoherence" OR “quantum communication" OR “quantum memory" OR “quantum memories" OR “quantum repeaters" OR “quantum state transfer" OR “quantum zeno dynamics" OR “qubit" OR “qutrit" OR “qudit" OR “quantum correlations" OR “quantum entanglement" OR “quantum discord" OR “quantum noise engineering" OR “quantum state engineering" OR “quantum protocols" OR “quantum annealing” OR “quantum logic gate” OR “quantum internet” OR “quantum repeater” OR “quantum memory” OR “quantum photonics” OR “quantum photonic” OR “quantum biology” OR “quantum machine learning”) NOT (“qubit fluorometer”))

PART II

Article 1.1: The landscape of the quantum start-up ecosystem[83]

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Abstract

The second quantum revolution has been producing groundbreaking scientific and technological outputs since the early 2000s; however, the scientific literature on the impact of this revolution on the industry, specifically on start-ups, is limited. In this paper, we present a landscaping study with a gathered dataset of 441 companies from 42 countries that we identify as quantum start-ups, meaning that they mainly focus on quantum technologies (QT) as their primary priority business. We answer the following questions: (1) What are the temporal and geographical distributions of the quantum start-ups? (2) How can we categorize them, and how are these categories populated? (3) Are there any patterns that we can derive from empirical data on trends? We found that more than 92% of these companies have been founded within the last 10 years, and more than 50% of them are located in the US, the UK, and Canada. We categorized the QT start-ups into six fields: (i) complementary technologies, (ii) quantum computing (hardware), (iii) quantum computing (software/application/simulation), (iv) quantum cryptography/communication, (v) quantum sensing and metrology, and (vi) supporting companies, and analyzed the population of each field both for countries, and temporally. Finally, we argue that low levels of quantum start-up activity in a country might be an indicator of a national initiative to be adopted afterwards, which later sees both an increase in the number of start-ups, and a diversification of activity in different QT fields.

Keywords: Quantum technologies; Start-up ecosystem; Landscaping study; Emerging technologies

1. Introduction

For over the last two decades, the second quantum revolution [1] has been ongoing with increasing global interest. Since the early 2010s, many of the large economies such as the UK [2], the US [3], France [4], Germany [5], Russia [6], India [7], and China [8] initiated national programs to support the development of quantum technologies (QT). In addition to the national programs, regional initiatives such as the EU Quantum Flagship [9], and international collaboration within greater contexts, such as the promise of increased collaboration on QT

[83] https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-022-00146-x

under AUKUS [10], have been happening in the last few years. These are being accompanied by a sharp increase in both the number of academic publications [11], the number of patents granted [12], and overall investments [13], which have led to an increased amount of private funding in a period some refer to as the 'quantum gold rush' [14]. The expected public investment to QT within the next five to ten years is more than 20 billion euros [15]. In just a decade, QT became a contender for being the 'next big thing' from a topic discussed mainly in physics conferences.

All these activities are also accompanied by an increase in the number of start-ups being founded, and an ecosystem rapidly growing. Some aspects of the QT ecosystem in general have been studied in the literature, such as the skills and knowledge needed for the required new workforce [16], and the temporal consultancy work within the growing QT market [17]. Furthermore, there are many studies focusing on applications of QT and its subfields, such as industry [18] and commercial [19] applications of quantum computing, quantum computing for finance [20, 21], chemistry [22], and so on. Similarly, there are many studies on sectoral applications of QT like for space [23], telecommunications [24], and military [25]. However, a study on the emerging landscape of the quantum start-up ecosystem has been missing in the literature.

In this paper, we aim to answer several essential questions regarding the evolution and properties of this emerging landscape:

1. What are the temporal and geographical distributions of the quantum start-ups?
2. How can quantum start-ups be categorized, and how are these categories populated?
3. What type of patterns can be derived from empirical data on trends?

2. Methods

In this section, we provide information on how the dataset of quantum start-up companies were compiled, how they were categorized under six subfields, and the limitations of our methods.

2.1.Dataset

The dataset utilized in this study was created between September 2017 and September 2022 with gradual additions. We mainly used publicly available resources such as websites, LinkedIn profiles, targeted Crunchbase searches [26], and other databases. There were several ordered lists of companies that we utilized as resources, such as the lists in at Understanding Quantum Technologies document by Olivier Ezratty [27], the Private/Startup Companies section of the Quantum Computing Report website [28], The Quantum In- sider platform [29], QIS Data Portal [30], and several consortium member lists such as Quantum Industry Canada (QIC) [31], The Quantum Economic Development Consortium (QED-C) [32], European Quantum Industry Consortium (QuIC) [33], UKQuantum [34], Quantum Technologies Development Consortium (QTC) in Israel [35], Quantum Technology and Application Consortium (QUTAC) in Germany [36], MSU Quantum Technology Centre in Russia [37], Quantum Business Network in Germany [38], and IBM Quantum Network [39]. Furthermore, in years we added start-ups to our database from the participant lists of events like Inside Quantum Technology [40], Quantum Business

Europe [41], Q2B [42] organized by QCWare, and Careers in Quantum Technologies organized by QURECA [43].

First of all, we wanted to correctly depict the evolution of the dedicated quantum startup ecosystem; hence, we aimed at excluding all companies that only approached QT as a secondary business or focused on it only later in their company history. Our aim was to minimize the number of false positives in our database. It was easy to identify and exclude major corporate players such as IBM and Google. It was also easy to identify many of the start-up companies that were operating in adjacent fields, such as photonics, nanotechnology or cybersecurity, and getting into the quantum field. There were some borderline cases, start-up companies that started in an adjacent field but transitioned to prioritizing QT in recent years. To identify these, we used the WayBackMachine provided by the non-profit Internet Archive [44] to check previous versions of the company websites, and look for explicit references to QT or closely related products (like single photon sources- detectors, cryogenic systems, quantum dots, etc.).

Secondly, we wanted to identify the countries and founding years of these start-ups as accurately as possible. This especially became a priority after encountering numerous contradicting information on publicly available databases. Therefore, we adopted the following double-check mechanisms: (i) checking when the website was founded via WayBackMachine, (ii) checking LinkedIn profiles of one or several founders, (iii) checking news articles (especially useful for university spin-offs), and (iv) checking seed or series A funding news if there are supporting venture capital firms. Sometimes more informal methods, such as asking an employee or a founder the founding date of the company, were also employed.

Thirdly, for the country of the start-ups, if the company moved after its founding, we considered the original country as the ‘Country’ of our start-up. This was a deliberate choice to avoid any bias that might be carried on by the date data gathering was stopped. Also, we believe that a company’s origin country has more explanatory value in identifying the global distribution of expertise and interest, and a company’s operating country has more explanatory value in depicting the current market maturity levels. Researchers interested in market activity are welcome to utilize and alter our dataset with a quick check on each start-up.

Finally, during this paper we refer to all the new companies that were founded with a particular focus in the QT as quantum start-ups, regardless of their age. This is due to our analysis mainly focusing on the founding of these companies, rather than their performance, longevity, or other qualities. For the dataset, we acknowledge that there are some companies that shut down their operations, and others that were acquired by larger companies, and a few that went through mergers. We did not incorporate this information into our dataset, again for the same reason above. Formation of a start-up is an indicator of at least some expertise and interest in that country. Similarly, shutting down operations, acquisitions, and mergers are markers for different types of market activities, and although these might bear insightful fruits for innovation studies purposes, they are beyond the scope of our study.

2.2 Encoding

After compiling the dataset, we went through the process of assigning a main field of operation to each start-up. Following the US framework [3] we divided QT into three main subfields quantum computing/simulation, quantum cryptography/communication, and quantum sensing and metrology. After this, due to the levels of high activity in quantum computing, we divided it into two subfields of quantum computing (hardware) and quantum computing (software/application/simulation). Additionally, we added two more fields to cover companies that could not be listed under these previously mentioned four fields, and those were complementary technologies, and supporting companies. So, in the end, we had the following six fields: (i) complementary technologies (sometimes also referred to as enabling technologies), (ii) quantum computing (hardware), (iii) quantum computing (software/application/simulation), (iv) quantum cryptography/communication, (v) quantum sensing and metrology, and (vi) supporting companies.

Complementary technologies cover start-ups developing cryogenic systems, control electronics, vapor cells, and similar products that particularly aim to enable QT devices. Quantum computing hardware companies are those that focus on developing the hard- ware of quantum computers (usually qubit technologies) relying on different types of physical systems such as ion traps, superconducting systems, photonics, silicon, diamonds, and others. Quantum computing software/application/simulation field includes companies from those developing sector-specific applications (like finance) to companies working on quantum software development (such as compilers). For the quantum cryptography/communication field, we decided to include dedicated post-quantum cryptography (PQC) companies, in addition to the expected quantum key distribution (QKD), quantum encryption, and quantum network companies. The quantum sensing and metrology field includes both types of companies that are developing quantum sensors and the ones that utilize quantum sensors for sector specific solutions. Finally, supporting companies are start-ups that exist solely for purposes like consulting, education, event organization, and incubators. For visualization, we used *ggplot2, ggforce, RColorBrewer, dplyr*, and *forcats* packages in the R programming language. We used color blind friendly palettes when possible.

2.3 Limitations

There are three main limitations of this study. First, although we believe our dataset to be highly representative, we cannot argue that it is exhaustive. There are start-ups with no online activity. This is particularly true for non-English speaking countries. Therefore, it should be noted that the database biases Western countries, especially the English speaking ones. Secondly, the exclusion principles upheld here can easily be challenged. One might argue that a start-up that now focuses on QT should be accepted as a quantum start-up, which is as valid as our claim. We aimed at keeping the false positives near zero, which might have yielded an increased number of false negatives, and caused the exclusion of legitimate quantum start-ups. Hence, this limitation of arbitrariness in where the line is drawn should also be acknowledged while considering our outcomes and analysis. Finally, although here we focused on the number of start-ups to describe the landscape of the quantum start-up ecosystem, investment, valuation

sizes, and similar parameters can also be included as additional layers of analysis. Therefore, one should keep in mind the limitations of this study while assessing its conclusions.

In the next section, we present the key properties of our dataset and the outcomes of our analyses.

3. Results

Our dataset covers 441 companies in 42 countries that mainly focus on QT as their primary priority business. The oldest companies covered in our dataset are D-Wave Systems and MagiQ Technologies, which were founded in 1999. Therefore, the dataset covers 23 years of data between 1999-2022. We did not include corporate divisions (like IBM Quantum or Google Quantum AI Lab) in our dataset, and focused on and included companies that were founded as start-ups in QT.

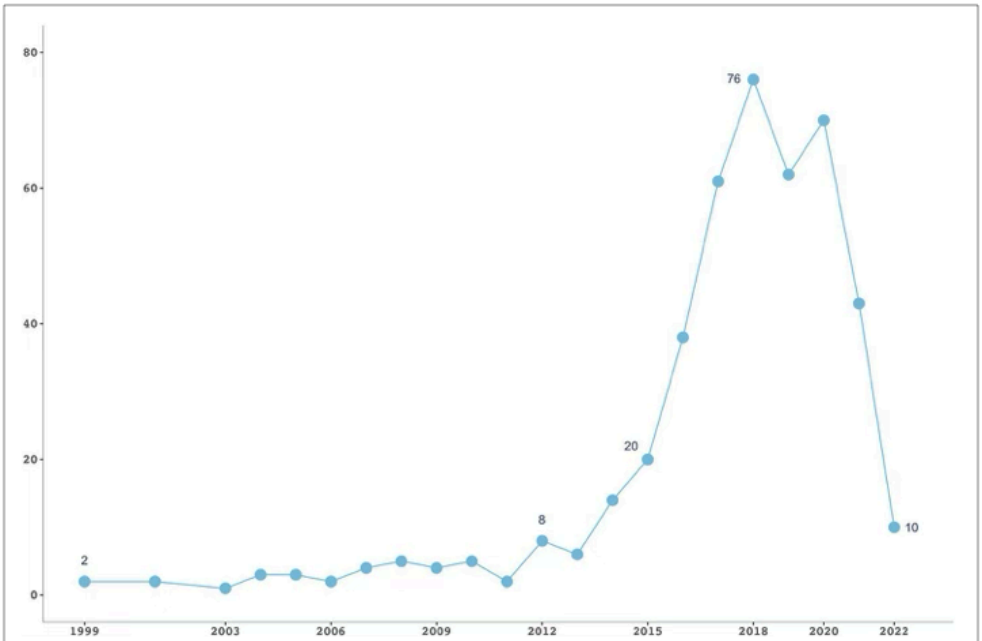


Figure 1 Number of new quantum start-ups per year

In Fig. 1, the yearly distribution of new start-ups per year is given. In our dataset, it appears that the number of start-ups founded has increased sharply starting from 2013, peaked in 2018, and has been slightly declining ever since (Fig. 1). In Fig. 2, the global distributions of these companies are provided. Though it might be important to keep in mind that our dataset does not cover stealth start-ups with zero visibility and has a lower representation of start-ups from non-English speaking countries. This can also be observed in the global distribution of start-ups (Fig. 2), as the majority of companies in the dataset are from the US, Canada, and the UK.

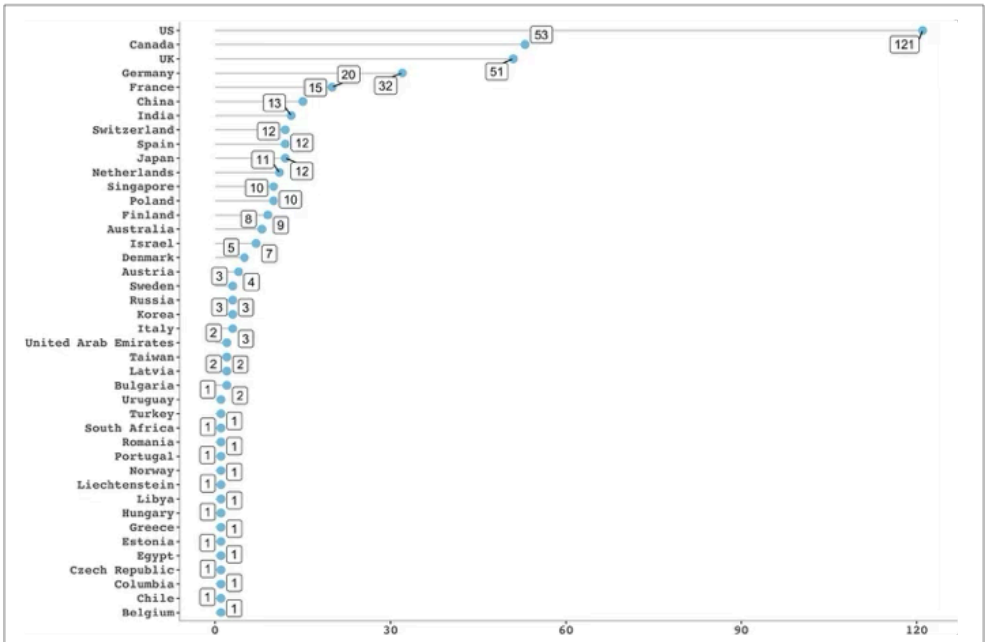


Figure 2 Number of quantum start-ups in countries

Next, we checked the yearly distribution of new start-ups with respect to different fields. In Fig. 3, the violin plot shows the temporal distribution of startups in fields. The areas inside the curves add up to the total number of start-ups in respective fields.

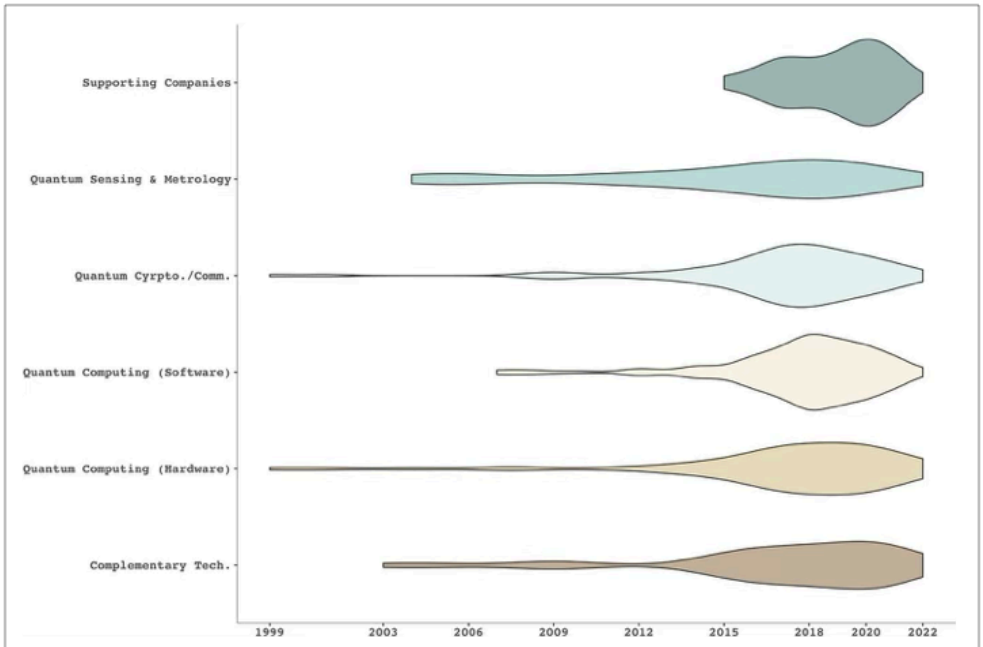


Figure 3 Violin plot of new quantum start-ups per year in different fields

It can be seen from Fig. 3 that almost all fields have experienced a surge of interest in recent years, although there has been some activity in the field since the early 2000s. The most uniform temporal distribution can be seen in the quantum sensing and metrology field, while the most skewed distribution is for the supporting companies. This can also be observed in Fig. 4, where we looked at numbers per year in different fields instead of ratios.

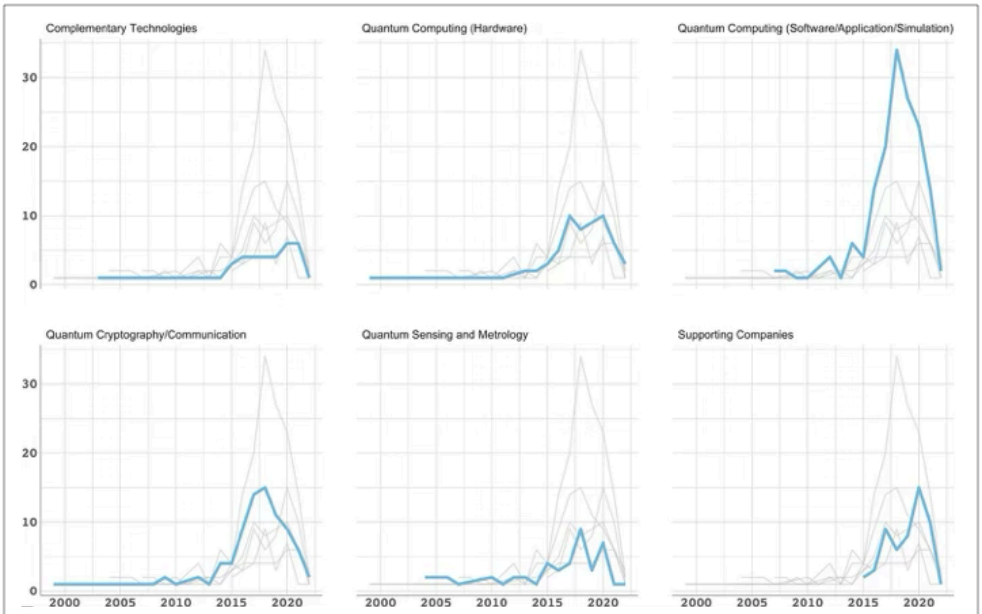


Figure 4 Number of new quantum start-ups in their respective fields per year

Following this, we checked the global distribution of startups in different fields in Fig. 5. It can be seen that the most diverse fields (where a high number of countries are active) are quantum computing (software/applications/simulation), quantum cryptography/communication, and supporting companies. The least diverse fields are quantum sensing and metrology, and complementary technologies. Although, regardless of diversity, the US leads in the number of start-ups in every field, while the second place varies between fields. For example, Canada has the second most start-ups in both quantum computing fields (hardware and software/applications/simulation), while the UK has the second place in the quantum sensing and metrology, and the quantum cryptography/communication fields. Lastly, in the complementary technologies field, Germany and Netherlands are competing for second place.

Afterwards, we checked the global distribution of start-ups in different fields in Fig. 6. For the top five countries (the US, Canada, the UK, Germany, and France), it can be seen that each six fields are represented. However, as we go down the line, it becomes less frequent. We can see that in some countries, only supporting companies exist. Furthermore, there is no apparent pattern across the countries in the ratios of start-ups operating in different fields.

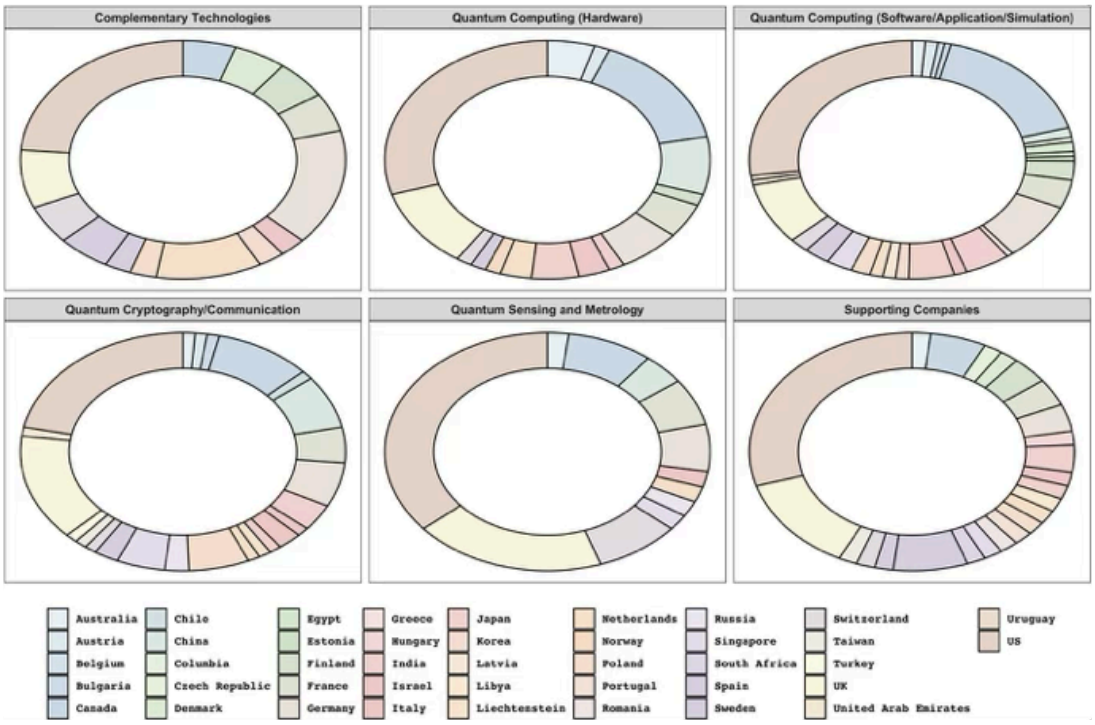


Figure 5 Pie chart of each field with ratios of countries represented in different colors

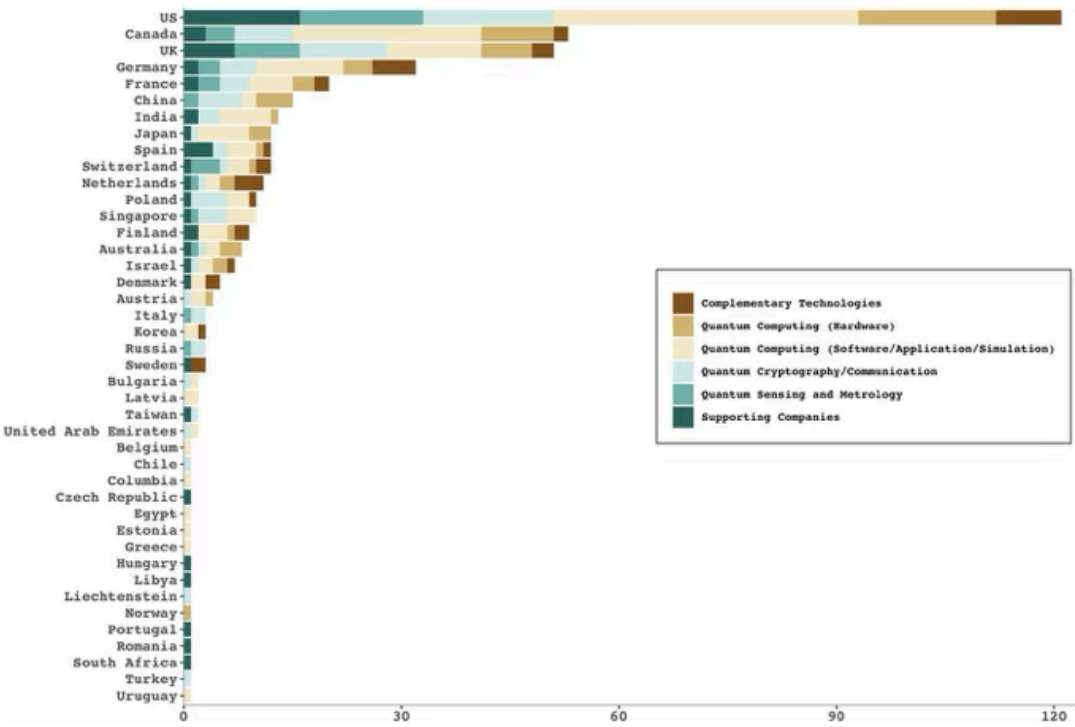


Figure 6 Number of quantum start-ups in countries in different fields stacked

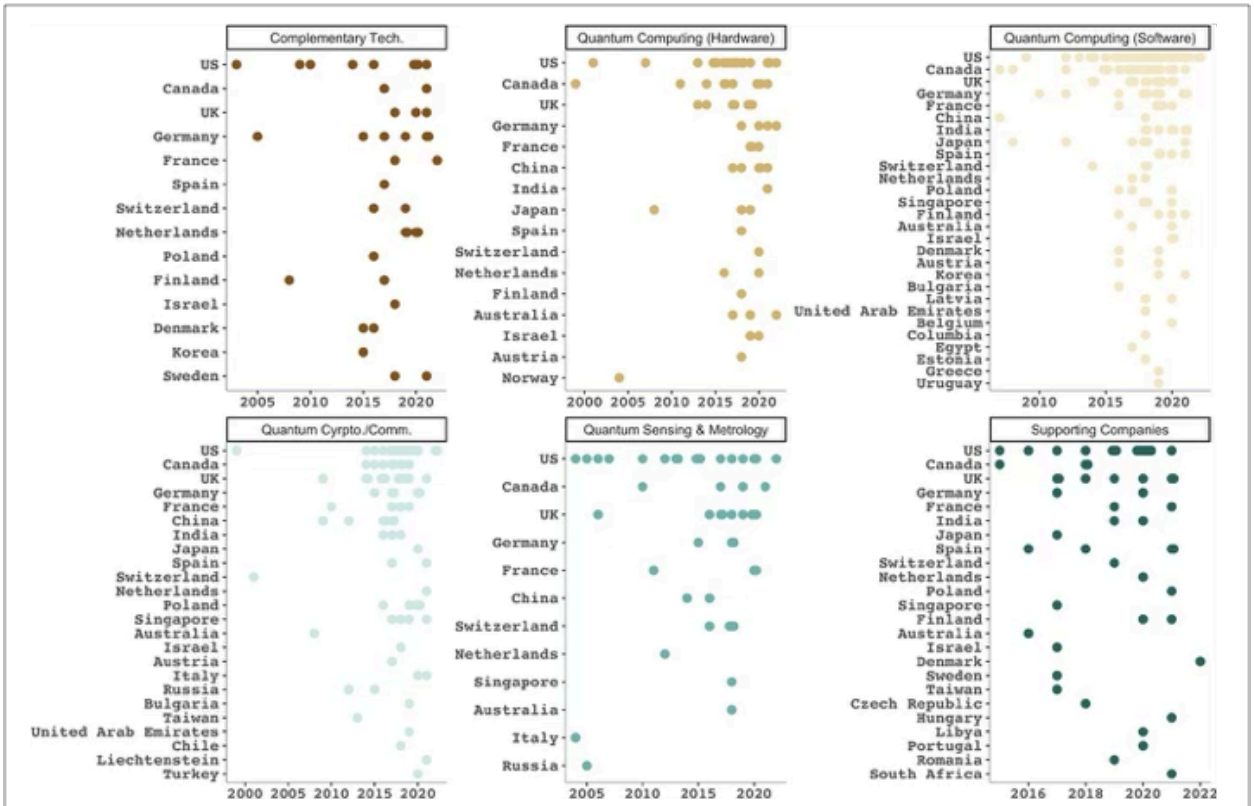


Figure 7 Yearly frequency of companies founded for each country to identify emerging interests in fields

In Fig. 7 we present the information on which and when fields have been emerging in which countries. It can be seen that in the US and the UK, supporting companies have been the emerging trend for the last several years, while in other countries, the trends vary widely. This is particularly useful to see in countries with a low number of start-ups, which field was introduced when. It can be seen that almost half of the countries in the list had their first start-up in quantum technologies following 2015, and the level of activity in countries with already one or few start-ups has highly increased since 2015. However, it can be seen that in a handful of countries, there has been activity since the mid-2000s, and in the US, there has been almost continuous activity since the early 2000s.

Following the country based analysis, we clustered the start-ups founded in different regions for a global comparison of regions versus countries. This was particularly conducted to compare the EU-27 to the US, Australia, Canada and the UK (acronymed as AU-CA-UK), and the rest of the world (acronymed as ROTW). Two figures were created for comparison. In Fig. 8, we compare the total number of companies founded in these regions, and in Fig. 9, different fields in a stacked graph.

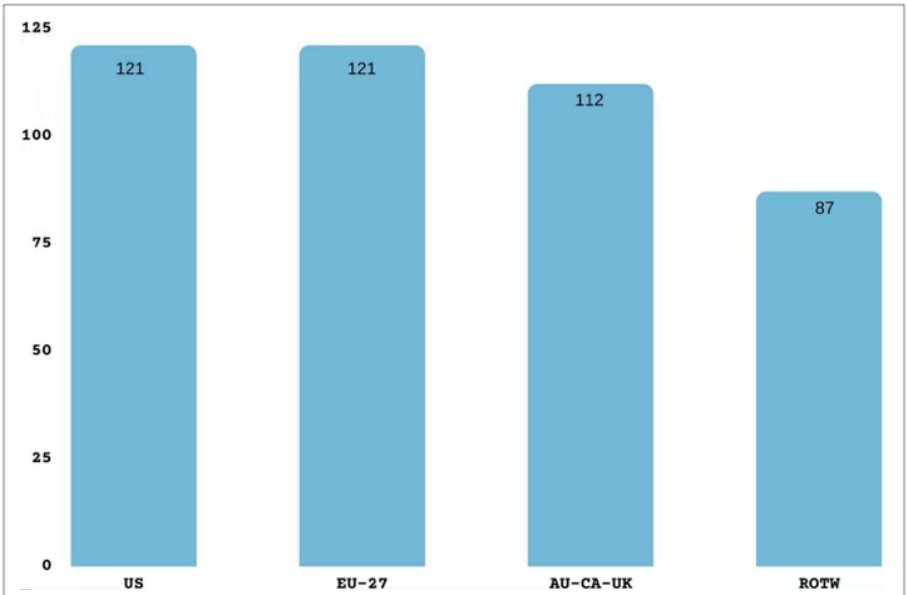


Figure 8 Total number of quantum start-ups founded in different regions

Figure 8 demonstrates the additional insights that can be gained by comparing regions instead of countries. Here, it can be seen that in terms of sheer numbers of companies the US, the EU-27, and the AU-CA-UK are operating on similar levels. Meanwhile, the rest of the world does not possess that many start-ups. This can be related to the limitations of our dataset, the fact that start-up culture is more adopted by certain regions, some other factors or a combination of these.

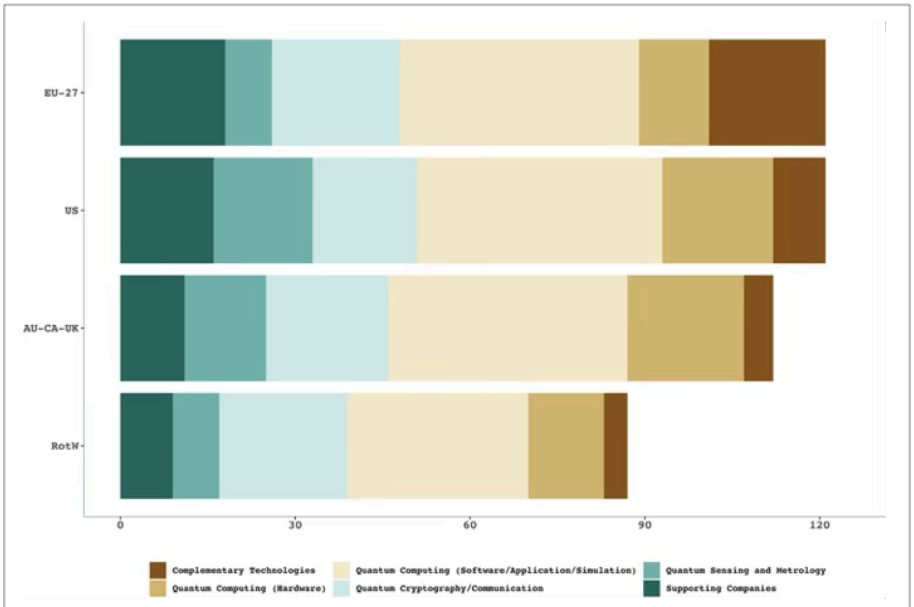


Figure 9 Number of quantum start-ups in regions in different fields stacked

Finally, in Fig. 9, we present the type of companies in different regions. It can be seen that the EU-27 has more supporting companies, start-ups focusing on complementary/enabling technologies and quantum cryptography/communication start-ups, while the US has a strong lead compared to the EU in quantum sensing and metrology, and quantum computing hardware start-ups. This figure shows that the adoption of different fields of QT varies on regional levels, however, all regions have presence in all the fields of QT.

4. Discussion

There are several quick answers that we can derive from the data presented above to our research questions. First of all, the temporal distribution of the quantum start-up ecosystem is not uniform; more than 92% of the companies we identified as quantum start-ups have been founded within the last 10 years, 68% in the last 5 years. Similarly, for the geographical distribution, more than 50% of the start-ups are located in the US, the UK, and Canada. Although there are 42 countries in our dataset, only half of them have more than two start-ups. We can say that the phenomenon of the quantum start-up ecosystem is both recent and limited in its global adoption.

Secondly, we categorized the companies under six fields, and investigated how these fields are populated. It can be seen in Fig. 3 that the most uniformly populated field is quantum sensing. Furthermore, it can be argued that there are established companies that are filling the market gap that might provide the necessary incentive for a start-up to be founded. We observed this while gathering data, as several measurement device manufacturers adopted QT-oriented products as one of their primary businesses, and we had to go back in their corporate history to identify whether they were quantum start-ups from the beginning; if not, we excluded them from the dataset. In Fig. 3 and Fig. 4 it can be seen that all fields were most active in the period after 2016, which again is not surprising since both the EU Flagship [9] and the US National Quantum Initiative [3] were kicked off in 2018, signaling that there will be increased market activity and funding opportunities in the following years.

Thirdly, a phenomenon to be observed regarding the categories is the emergence of a field of ‘Supporting Companies’. The consultancy aspect of this phenomenon was also addressed previously in the literature for quantum computing in a qualitative manner [17]. Here, our data clearly shows the emergence of supporting companies around the newly established QT sector. The businesses of these companies are mainly consultancy, ecosystem support/development, reporting, event organization, and education. As the needs of the quantum industry [16] diversify, it is only natural that the supporting ecosystem becomes diverse in the services they provide to this rapidly growing sector.

Fourthly, there are two clear patterns from the gathered data that we observed. First, the number of countries that contain interested entrepreneurs toward QT has been increasing, especially since 2016. Additionally, it appears that low levels of start-up activity usually precede the formulation of national initiatives, and the number of start-ups rises after such initiatives are announced. In the light of this observation, it can be proposed that for a country to formulate a

national initiative, having one or two start-ups in the QT domain is usually a precursor or a catalyst. Furthermore, if this can be generalized, we can expect national initiatives in more than 20 countries where start-ups emerged following 2016, and that does not have a national initiative focusing on QT. Secondly, 38% of countries possess QT start-ups that are operating in four or more fields of QT, indicating a diverse set of activities in QT. This by itself is not an indicator that different fields in QT are supporting each other, but remembering from Fig. 5 and Fig. 7 that almost all fields have certain levels of globally diverse start-up actors. To summarize this point, low levels of activity might be an indicator of a national initiative for a country, which later sees both an increase in the number of start-ups, and a diversification of activity in different QT fields.

Fifthly, it should be noted that not all start-ups are created equal. For example, PsiQuantum, a photonic quantum computing hardware manufacturing company, has raised over 600 M$ in its funding rounds [45] or IonQ, a publicly-traded ion trap quantum computing hardware manufacturing company, is valued almost around 2 B$ [46]. On the other hand, many of the start-ups have much lower seed funds or initial investment amounts [47].

Sixthly, an open question in the QT ecosystem development predictions is whether there is room for further diversification or if the time for consolidation is soon. We recently started seeing mergers in the field, such as Honeywell Quantum Solutions and Cambridge Quantum [48], and Pasqal and Qu&Co [49]. Also, there have been partial acquisitions, such as SK Telecom buying out the majority share of ID Quantique [50]. There have also been special purpose acquisition company (SPAC) deals like IonQ [46], Rigetti [51], and D-Wave [52], which attracted hundreds of millions of dollars each, but also potentially created new hurdles for the companies such as more public scrutiny and hostile reports by short-sellers [53]. As discussed in the literature previously, the quantum gold rush [14] caused the attraction of private funding to the field in many shapes and forms. However, the phenomenon of acquisitions, mergers, and SPACs appear to be recent, which followed the increased interest in the QT domain following 2016. Additionally, there are new mechanisms to support diversification, such as the European Innovation Council (EIC). Previously, EIC supported three companies in the QT field [54] and for 2022 there is an open Pathfinder Challenge in “Alternative approaches to Quantum Information Processing, Communication, and Sensing” with an approximately €28M [55] budget. Therefore, the question of whether the trend of diversification will continue at this rate or whether consolidation will become the modus operandi of the field is a question directly related to whether further increase in interest from countries and private investment sources are possible or not. The idea of a possible quantum winter, especially in quantum computing [56], has been discussed previously. Our data does not clearly provide any answers in one way or another; however, running a similar analysis in two or three years and comparing with ours might allow further insight, especially on the question of whether 2018 was a true maximum, or that we are just missing data due to the limitations listed in the Methods section.

Seventhly, we expect a further expansion of categories will become necessary as the field progresses. Within the field of quantum cryptography/communications, there are companies that are engaged in PQC, QKD, quantum encryption, and quantum networks. The timelines of these

subfields vary, hence, as the number of start-ups and market activity increases, this field is probably going to require a division into three subfields; PQC, quantum cryptography, and quantum communication. A similar argument can also be made for the quantum sensing and metrology field, since it encompasses companies operating in increasingly separate areas of activity.

Eightly, it is clear from Fig. 8 and Fig. 9 that regional level analysis offers additional insight on top of the country level analyses. However, reaching conclusions from regional level analysis require further investment into identifying the appropriate regional clusters. In this work, we focused on comparing the EU-27 with the US and AU-CA-UK as potential market competitors, but the relationship between these regions and the clustered countries deserve a dedicated analysis. Our preliminary findings here reflect that there are regional differences in preferences towards certain fields of QT, but there is diversity of companies in terms of fields within each region.

Finally, while gathering data, we noticed the emergence of a new group of organizations within the quantum ecosystem, which are non-profit organizations and similar supporting entities. There are several consortia of organizations mainly aiming at industry goals; Quantum Industry Canada (QIC) [31], The Quantum Economic Development (QED-C) in the US [32], European Quantum Industry Consortium (QuIC) [33], Quantum Technology and Application Consortium (QUTAC) in Germany [36], UKQuantum [34], Quantum Ecosystems Technology Council of India (QETCI) [57], Quantum Technologies Development Consortium (QTC) in Israel [35], Quantum Innovation Initiative Consortium (QIIC) in Japan [58], and the Consortium organized around the Lomonosov Moscow State University in Russia [37]. There are non-profit organizations with education and outreach purposes like QWorld [59], One Quantum [60], Q-munity [61], Feynman Foundation [62], and Quantum AI Foundation [63]. There are supporting organizations like Unitary Fund [64] and Quantum Open Source Foundation [65]. Finally, there are incubators and similar initiatives supported by local governments such as the Munich Quantum Valley [66] in Bavaria/Germany, the Quantum Algorithms Institute [67] in British Columbia/Canada, and Chicago Quantum Exchange [68] in Illinois/US. We believe that a landscaping study on the ecosystem comprising these organizations is also required as both the number of organizations, and their intertwinement with the rest of the ecosystem appears to be growing.

5. Conclusion

In this paper, we presented the gathered dataset of 441 companies from 42 countries that we identified as quantum start-ups, meaning that they were founded as companies mainly focusing on QT as their primary priority business. Following this, we answered some questions on temporal and geographical distribution of these start-ups, their categories, and patterns emerging from their analysis.

As a descriptive study, we hope this article can act as a good foundational work for future studies. The dataset can be improved by adding further information on companies like their size, valuation, investment amounts, and other aspects. Similarly, each field deserves more in depth

analysis of its dynamics, and some questions are raised here such as the effects of the emerging cohort of supporting companies, whether the start-up activity can actually be connected to following policy decisions (in the form of national initiatives or programs), and what are the path-dependencies that are currently being set which will limit the opportunity space of future development of the field. Start-ups are considered to be an important aspect of the emerging ecosystem of QT [69], and exploring such questions can lead to a better-informed understanding of further steps to be taken.

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Abbreviations
EIC, European Innovation Council; PQC, Post-Quantum Cryptography; QT, Quantum Technologies; QED-C, Quantum Economic Development Consortium; QuIC, European Quantum Industry Consortium; QUTAC, Quantum Technology and Application Consortium; QKD, Quantum Key Distribution; SPAC, Special Purpose Acquisition Company.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

Author contributions
Z.C.S. constructed the dataset, and wrote the main manuscript text. R.K. ran analyses and prepared the figures. A.U.A. guided the research, provided theoretical background, and edited the manuscript. All authors reviewed the manuscript.

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Article 1.2: Global innovation and competition in quantum technology, viewed through the lens of patents and artificial intelligence[84]

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Abstract: In this work we elucidate international trends in the field of quantum technology (QT) by analysing a global patent database built from an operational definition of QT that was generated through the curated application of artificial intelligence (AI). In doing so, we demonstrate how the sophisticated use of intellectual property information, enhanced by the artful deployment of AI techniques, may produce more reliable and useful revelations for policymakers and managers about global innovation in emerging fields of technology than is possible through conventional methods of data collection and analysis. We also demonstrate the utility of this approach for reliably characterising the evolving constituent sub-fields of QT. By adopting a hybrid human-AI approach to both the definition and the analysis of QT, we have produced some novel insights about global innovation and national organisational profiles in the QT field, particularly concerning dynamic competition between the USA and China.

Keywords: quantum technology; quantum innovation; patent analysis; artificial intelligence; patent landscape; patinformatics; global technological innovation; quantum competition; quantum industry.

1. Introduction

Quantum technology (QT) is a field of innovation attracting global attention in recent years. Two initiatives, each in the order of one billion Euro (€1B), were recently enacted by the EU (Riedel et al., 2019) and the USA (Raymer and Monroe, 2019). Similar programs exist, all initiated within the last decade, in Canada (Sussman et al., 2019), Japan (Yamamoto et al., 2019), Australia (Roberson and White, 2019), the UK (Knight and Walmsley, 2019), Russia (Fedorov et al., 2019), and China (Zhang et al., 2019). The combined planned investment through such initiatives worldwide is currently around €20B (Qureca, 2020). One of the main motivations for

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these initiatives is to support the commercialisation of quantum technologies, an activity that may be referred to as the 'out of the lab, into the market' approach.

These developments may be read as part of the ongoing 'second quantum revolution', a term coined in the early 2000s (Dowling and Milburn, 2003a), which covers (but is not limited to) technologies emanating from quantum information science. The main subfields of QT are generally characterised as quantum communication/cryptography, quantum computation/simulation, and quantum metrology/sensing. Besides the fact that QT has become a focal point for international investment and competition, why is this field of technology interesting for academic research about innovation? One reason is that while QT and quantum science have been heralded as one of the most important products of human society during the 20th century, with immense practical implications for society and the economy (Jaeger, 2018), exactly what constitutes QT is highly disputed and widely misunderstood. Concepts derived from quantum physics – such as superposition (in which a particle may be in two states, or places, simultaneously), quantum entanglement (whereby classically not-possible correlations can be shared between distant locations), quantum tunnelling (whereby a wave may pass through an ostensibly – according to classical mechanics – impenetrable barrier), or the replacement of absolute truth with probabilistic estimates – make QT not only difficult for people not deeply educated in quantum theory to understand, but also rather difficult to define. The intrinsic difficulty of reaching a widely accepted and precise definition of the concept of QT is amplified when seeking to operationally define QT for the purposes of industry analysis, public investment, or the assignment of intellectual property rights. If a national government wishes to allocate a billion Euro of public funds to QT, what are the actual decision parameters that a public official should use when allocating the funds? If a venture capitalist wishes to invest in QT, what criteria should be used to select appropriate ventures or projects for the firm's portfolio? In an attempt to address these intellectual-cum-practical challenges, we propose in this paper the use of a hybrid human-intelligence/artificial intelligence (AI) approach to 'naturally' defining the domain of QT based on the emergent way that the field has been treated by the world's patent offices in response to inventors in the field seeking exclusive rights for their inventions, i.e., for patents for the technological embodiments of quantum phenomena.

Although several bibliometric studies have been published focusing on the general field and subfields of quantum technologies (Bornmann et al., 2019; Dhawan et al., 2018; Olijnyk, 2018; Pande and Mulay, 2020; Seskir and Aydinoglu, 2021; Tolcheev, 2018), only a few academic studies investigating the patent landscape have appeared (Chang, 2005; Winiarczyk et al., 2013). One possible explanation is that patent data research relying on keyword searches and the use of cooperative patent classification (CPC) codes alone can easily yield 20% 'false positives' (and up to 80% in some cases), with the resulting risk that a significant number of patents belonging to other fields of technology may be falsely attributed to the domain of QT (Travagnin, 2019). To avoid this problem, we have utilised a recently developed supervised machine-learning method to create a new classification tool for quantum technologies to build a cleaner dataset for more accurate analysis.

Patent analysis studies can provide insights into certain aspects of a field such as technological maturity, commercial interest, market formation, and expectations by actors and stakeholders of returns. Furthermore, they can be used as inputs for higher-level analysis, for example on impact assessment for certain policies like industry-academia collaboration incentives. With these factors in mind, and in addition to the general motivation of our study – to employ a hybrid human-intelligence/AI approach to defining QT, focused on the analysis of patents – the research reported here was conducted with two primary aims. First, we aimed to paint a clearer picture of global patenting activities going on in QT, and to draw some preliminary conclusions from our initial analysis, especially on the distribution and the nature of patenting activities in and by the leading countries in the field. Second, we aimed to demonstrate that AI enhanced patent analysis can provide valuable insights about newly emerging fields of technology that are otherwise difficult or impossible to obtain through conventional searches using CPC codes and keywords alone.

2. Methodology

The methodology we employed to carry out our study relied upon three critically important procedures. The first was to develop a formal operational definition of QT based upon a comprehensive analysis of the semantic content of thousands of patents and published patent applications, using the actual substantive characterisation of the technology contained in the patent documents, rather than pre-conceived classifications based on standardised CPC codes or arbitrary or irregular use of keywords. We engaged in an iterative process, in multiple stages, involving the curated application of AI algorithms to gradually train an AI software system to recognise the distinctive features of an invention that made it a QT invention rather than a member of some other field of technology.

This process, a hybrid AI-human process, involved feeding the AI system with pertinent information in the form of patents in the field of QT obtained by well-known actors operating in the QT commercial landscape, and then systematically evaluating examples of QT patents identified by the AI system from a comprehensive global patent dataset covering all patents and patent applications published by patent offices from over 100 countries over the last several decades. In other words, the method required extensive interaction between intelligent humans who ‘trained’ the AI software to recognise examples of patents in the field of QT, and the AI system itself that presented to the human beings examples it found from published patent documents worldwide that fitted within the parameters of QT patents it had been trained to recognise at each iteration of the training process. The end result of this iterative process was a robust formal ‘definition’ of QT embedded into the AI software as a set of characteristic features of QT against which any published patent document – either a patent or a patent application – could be checked. The QT definition, which in effect is a software-embedded algorithm-based classification tool, is labelled for convenience here as a QT ‘classifier’. The overall process of training the AI system and producing the QT classifier – which entailed the careful checking of about 11,600 patent documents, and classifying over 5,000 of those documents as describing genuine QT inventions (i.e., as ‘positives’), and over 6,000 as failing to do so (i.e., as ‘negatives’ or false positives) – is described in detail in the Appendix.

Following completion of the first procedure – the creation of a formal operational definition of QT (i.e., the creation of a QT 'classifier') – we then applied the QT classifier to search the whole population of all patent documents worldwide published digitally online, in all fields of technology, to identify which inventions described in the global patent system matched our AI-curated definition of QT. We calculated the cumulative number of active QT patent families worldwide for the most recent 35 years. A patent family was defined as a single set of pending and granted patents worldwide for one invention in which at least one patent or application in the set had been published. Each patent family in our dataset was allocated to a particular year according to the filing date of the first patent application in the family. In this manner we were able to identify over 14,000 patent families worldwide that with very high confidence may be classified as belonging to the domain of QT, conservatively defined.[1] A detailed description of the second procedure is provided in Appendix.

For the third procedure, after having built the final dataset of verified QT patent families during the second procedure, we then applied the AI system to auto-generate technological subcategories from within the dataset itself, by utilising data from the title, abstract, and citations sections of patent documents. In other words, the AI system categorised the broad domain of QT in to sub-fields 'naturally' or endogenously using the internal language of the patent documents themselves – rather than by applying externally imposed classifications such as CPC codes – to characterise the diversity or complexity of the overall QT domain.

All three procedures in our methodology were carried out using a commercially available online patent information service, *Cipher*, developed by Aistemos Limited (2020). *Cipher* includes both the dedicated patent-related AI system itself (accessible as software-as-service over the cloud) and access to a comprehensive curated dataset of all published patent documents (patent applications and granted patents) worldwide for the most recent three-and-a-half decades. Details are provided in Appendix.

3. Profiling the field of QT using an AI-enhanced patent dataset

After completing construction of our robust and verified QT patent dataset, we conducted a series of analyses, commencing with calculating the number of QT inventions embodied in published patent documents each year since 1985.

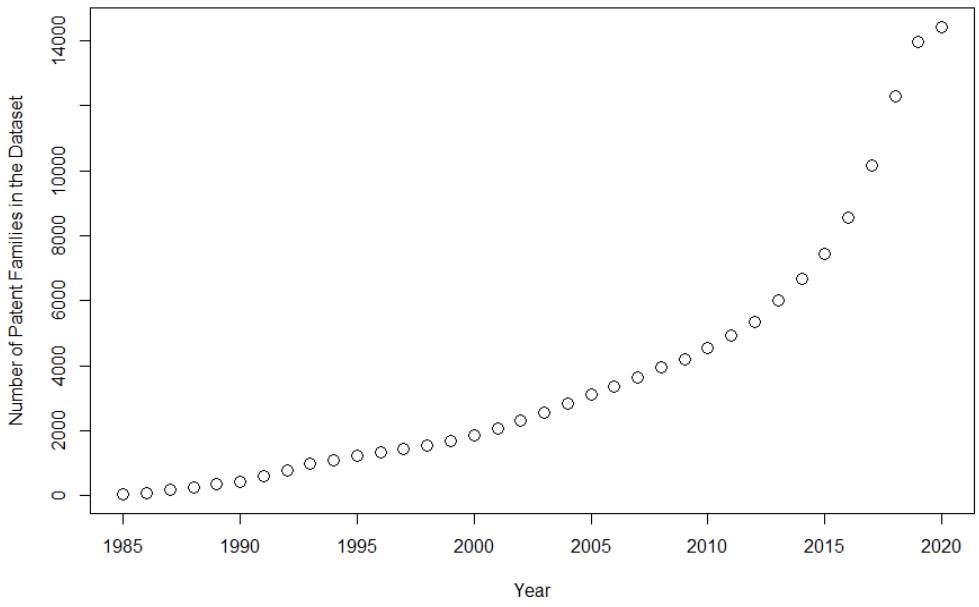


Figure 1 Cumulative number of QT patent families, by priority year

The basic results, plotted in Figure 1, reveal a generally linear increase in the number of patented QT inventions worldwide during the first two-and-a-half decades of the period included in the graph, followed by almost exponential growth during the most recent decade. The slight levelling in the graph line following 2019 is caused by the fact that most patent applications remain secret for 18 months following their filing date, and not because of a slow-down in the rate of new patent applications. The results confirm that QT is clearly a focus of burgeoning international commercial interest, not just a field of scientific inquiry and laboratory experimentation, and that the level of interest has accelerated during recent years.

Next, as indicated in the methodology section, we used *Cipher's* internal AI-based categorisation facility to create auto-generated technological subcategories. Out of the 12 top QT subcategories, the first five contained the vast majority (93%) of currently active patent families, and hence we focused on these and plotted the number of new patent families in each subcategory with respect to priority years. The results are shown in Figure 2, with the vertical axes representing the number of active patent families in each subcategory and the horizontal axes representing the priority year of each family. All five QT subcategories exhibited significant growth. However, it is notable that inventions in fields related to the subject matter of quantum computing, quantum cryptography, and quantum dot-based applications (mostly sensing) exhibit a dramatically higher number of patent applications than inventions related to single photon sources and photon detection systems.

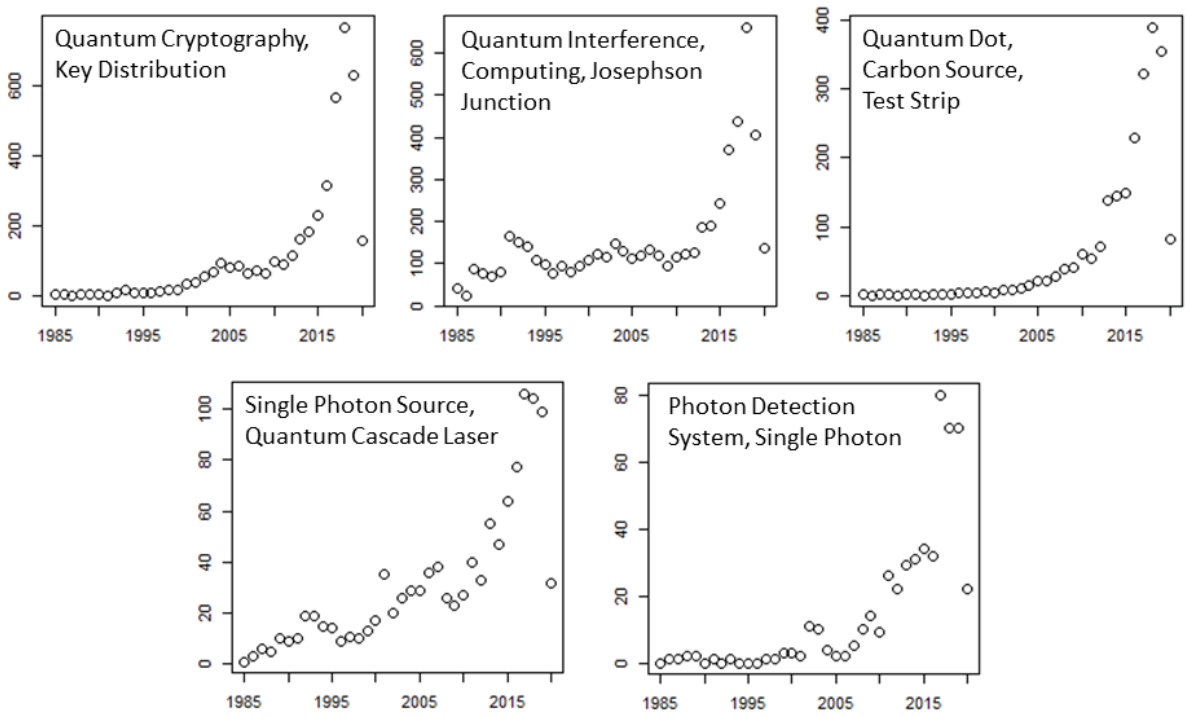


Figure 2 Annual number of new patent families (by priority year) for the five most dominant QT subcategories

Figure 3 presents a profile of the legal status of the patents in our dataset at the time it was completed (November 2020). In accordance with the protocol of *Cipher*, the basic unit of analysis in our dataset (unless otherwise stated) is the patent family, rather than the individual patent. Thus, if the initial patent application of a patent family (from which the priority date is set) is still pending, the patent family as a whole is registered in the system as pending even if a patent application for the same invention is granted or rejected in other countries. Similarly, if the patent which was the subject of the initial patent application of a patent family is granted, the patent family as a whole is registered as granted, even if a patent application for the same invention is pending or rejected in other countries. Likewise, a patent family in our dataset classified as 'expired' may nevertheless still appear in the results as an 'active patent family' if one or more patents in the family are still active. For example, if an organisation outside the USA applies for a patent in its home country, followed by a patent application for the same invention to the United States Patent and Trademark Office (USPTO), and then subsequently abandons its original application but has its US patent granted, then the patent family to which this invention belongs is classified as 'rejected' even though it contains a granted unexpired US patent.

Our QT dataset includes 2,411 'expired' patent families (meaning that there are 2,411 families which still contain active patents but in which the initial patent in the family has expired). The average time from the priority date to the expiration date of these patent families is 11.8 years, and only 14% of them exhibit less than five years between the priority date and the date of

expiration. This indicates that most of the active patent families in our dataset classified by *Cipher* as ‘expired’ were actually maintained with appropriate payment of fees for quite some time, and hence may be interpreted as having perceived value to their owners. The *Cipher* interface provides an estimated cost-to-date of a patent family in US dollars (US$), and this set of 2,411 patent families together possessed an estimated cost of over US$42 million. The estimated cost-to-date of the whole dataset of all 14,425 patent families is estimated by *Cipher* to be US$214 million, indicating that around 20% of the global spending on QT patent costs has been directed towards patents that are currently ‘expired’.

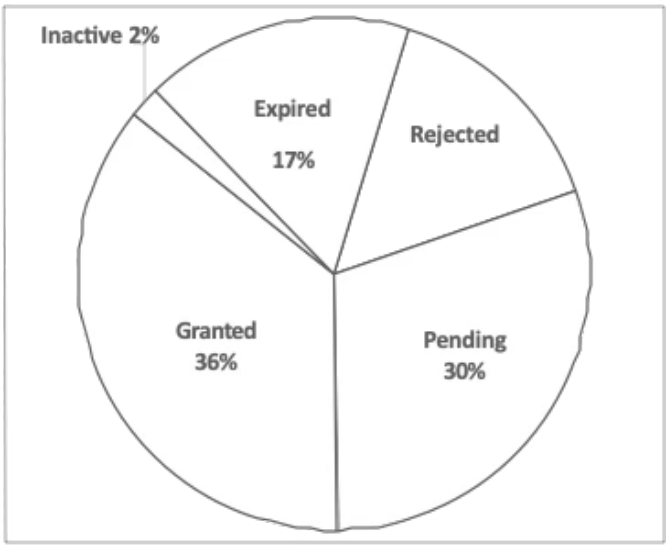


Figure 3 Distribution of patent status in the dataset of 14,425 QT patent families

Our dataset includes a total of 9,535 patent families classified with either a ‘granted’ or ‘pending’ status, and which together constitute roughly two thirds of all QT patent families identified by our classifier. As an additional check on the utility and robustness of the classifier, and with the goal of seeing whether the classifier inadvertently included high-profile patents unrelated to QT, we selected the top five patents in our dataset according to their estimated cost-to-date.

Table 1 Estimated cost-to-date of the top five patents in the dataset

Patent owner	*Patent title*	*Priority year*	*Cost to date (US$)*
Dolby Laboratories Inc.	Techniques for using quantum dots to regenerate light in display systems	2009	$425 k
D-Wave Systems Inc	Analog processor comprising quantum devices	2004	$253 k
Google LLC	Efficient network layer for IPv6 protocol	2013	$246 k

Google LLC	Constructing and programming quantum hardware for robust quantum annealing processes	2014	$238 k
University of California	SQUID Detected NRM and MRI at Ultralow fields	2002	$197 k

We were mildly surprised to discover that the most costly patent in our dataset (owned by Dolby Laboratories) happens to be related to the field of quantum-dot based display systems, since we had not consciously borne that field in mind when training the AI system to build the classifier. Nevertheless, the patent satisfied the 0.7 threshold fit score requirement we had adopted for the study and, upon careful examination of the patent document itself, we concluded that it should indeed be included in the dataset. A quick search revealed that out of 2,714 currently active patent families identified through a keyword search[2] as belonging to the field of quantum-dot based display systems, 170 were included in our dataset. After a manual check of this group of patents – which referred to inventions related to topics such as quantum-dot based LEDs, solar cells, and fabrication methods – we nevertheless decided to retain them in our dataset since for the most part they contained elements that belong within the general domain of QT. We also paid particular attention to the IPv6 protocol patent of Google, which ostensibly appeared unrelated to QT. However, it appeared that through a series of quantum related amendments made to an individual patent (AU2019275673A1) within the 'efficient network layer for IPv6 protocol' family, the family as a whole became associated with QT. For example, as illustrated by the following extract from its abstract, the patent contained several references to known quantum technologies: 'a quantum computational system, comprising an error corrector subsystem in data communication with measurement qubit ...' The other three patents listed in Table 1 are clear examples of quantum technologies. Our review of these five high-cost patents further assured us that our QT classifier is appropriate for reliably identifying patents across a variety of subfields of QT, internationally, regardless of their ostensible provenance or superficial appearance.

4. Insights about innovation in the QT domain

4.1 Comparison of QT patenting in China and the USA

Having confirmed the usefulness of our classifier through a variety of robustness tests, we conducted a comparison of QT patenting in the USA and China, which together hold the majority (55%) of the currently active individual QT patent grants worldwide (followed by Japan at 7%). A more detailed multi-national analysis of the country of origin of national patents is provided below (in Section 4.3), but here we focus on the temporal and quantity differences between the patent applications of the two most prominent countries, namely, the USA and China. Bearing in mind that patents pending are an indicator of likely future 'granted' patents, one of the most interesting differences between these two major players' lies with the relative numbers of their patent applications. China, although becoming an active source of patents in the field only after 2010, currently possess 30% of the active individual patent grants worldwide

compared to 25% in the USA. The temporal distribution of granted patents, combined with the high number of patent applications emanating from China (as shown in Figure 4), suggests that the future global balance may shift in the direction of China.

The above results evoke two lines of inquiry. First, how does the number of patents in each country translate into commercial impact? Second, who is actually doing the patenting and where are they doing it? To address the first question, two types of information in our dataset – namely, the type of patents and number of forward citations – may provide useful clues. Both of these measures may be seen as indicators of the quality and commercial potential of patents. China, unlike the USA, permits the granting of utility models, a type of patent with lower patentability standards, lower costs and a shorter time period of protection than normal patents (i.e., than 'invention patents' in China, or 'utility patents' in the USA) (Prud'homme, 2017). One criticism that is often levelled against patenting practice in China, and the rise of Chinese patents, is that they are of lower quality than USA, Japanese or European patents, in part because of the prevalence of utility models and the ease and low cost with which they may be obtained (Dang and Motohashi, 2015; Yang, 2014). One justification for this view is the belief that utility model applications in China are frequently filed not in expectation of commercial return or to protect unique intellectual assets but for other purposes, such as fulfilling KPIs or government mandated project goals. Although a similar argument could in principle also be directed towards US patent applications, the difference between the cost (excluding costs associated with patent searching and patent prosecution) of applying for a Chinese patent (around US$150) (European Commission IPR Hub, 2018) or Chinese utility model (around US$75) (European Commission IPR Hub, 2018) and applying for a US patent (around US$300 at minimum) (USPTO, 2020) is substantial. The difference is even greater when patent attorney costs are taken into account.

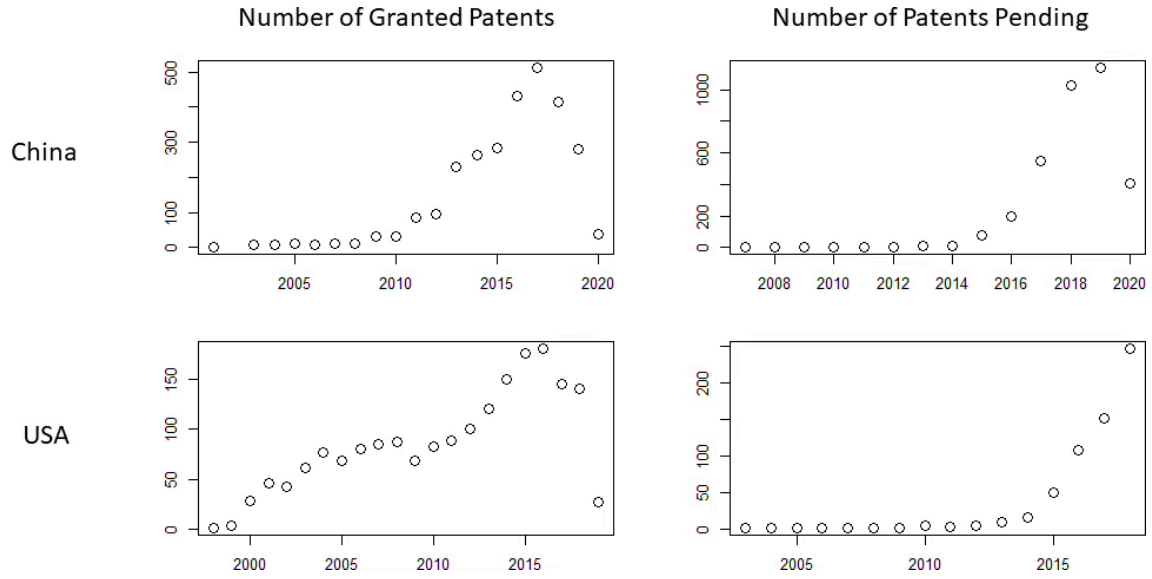


Figure 4 Comparison of granted QT patents and QT patents pending in the USA and China

Table 2 Comparison of currently active QT patent families in the USA and China

Patent-related comparison criteria	*USA*	*China*	*China (excluding utility models)*
Number of active patent families	1,870	2,814	2,062
Cost to date [$US] – total	$76 M	$36 M	$31 M
Future cost projection [$US] – total	$45 M	$44 M	$34 M
Average backward citations per patent	19	4	6
Average forward citations per patent	14	3	4
Average priority year	2011	2016	2015

Table 2 enables more subtle comparison of the QT patenting profiles of China and the USA, by presenting two versions of the China data, with one including and one excluding utility models. One interesting revelation that may be gleaned from Table 2 is that utility models account for not much more than one quarter (about 27%) of active QT patent families in China. While this figure is substantial (over 750 QT utility models) it is nevertheless clearly overshadowed by the number of 'real' QT patents. The average number of both forward citations and backward citations per document for utility models is much lower than for normal patents, which indicates that the presence of utility models most likely brings down the overall 'quality' of the national QT patent portfolio in China. Additionally, differences in the average priority date of normal (invention) patents and utility models as shown in Table 2, with the average date for utility models being more recent, suggesting that the proportion of Chinese patents accounted for by utility models may increase in the future, perhaps thereby further lowering the overall quality of the Chinese QT patent stock. This factor may be counterbalanced, however, by the fact that utility models expire earlier than normal (i.e., 'invention') patents in China, and by evidence that the overall quality of patents in China may in fact be increasing over time, due to public policy, corporate awareness and natural learning (Dang and Motohashi, 2015; Prud'homme, 2017; Yang, 2014). Thus, the relative future contribution of China to the QT field may be much more significant than widely presumed.

If one accepts the widespread understanding in the literature that highly cited patents tend to have higher market value than less cited patents (Hall et al., 2005), then it appears from the data in Table 2 that QT patents in the USA tend to be superior to those in China in terms of both quality and market value. This concurs with other published research showing that Chinese-originated patents (in general, across all fields) tend to suffer from a large citation lag in comparison to non-Chinese patents, suggesting a lower value, especially for patents filed domestically (Fisch et al., 2017). However, there is also empirical support for the view that the average value of Chinese patents has been increasing in recent years and that the value gap between Chinese and foreign patents might be narrowing over time (Fisch et al., 2017). Secondly, there is an average of four years of difference between two sets and, as presented in

Figure 4, the number of patents pending in China is quadruple the number in the US. At this point, while it appears that the USA outperforms China in terms of the quality of their respective QT patent portfolios, China outperforms the USA in terms of quantity, and there is no guarantee that such simple comparisons may be maintained. The sheer growth in the volume of Chinese QT patent applications, combined with evidence of improvements in patent quality over time, and taking in to account that the vast majority of Chinese QT patent families are based on normal (invention) patents rather than utility models, suggests that the USA lead in quality might not necessarily be maintained in the long term.

4.2 QT patenting behaviour of top organisations

Following the second line of inquiry, we looked at the currently active and granted individual patents per country, for the top 99 QT-patent owning organisations.[3] These 99 organisations together hold 6,257 out of the total of 9,781 active individual patents. We manually assigned each organisation to a country and organisational type. We assigned countries to global organisations with respect to their headquarters. For organisational 'type' we differentiated between four types of organisations:

- quantum start-ups
- established companies expanding into quantum technologies
- academic institutions
- public organisations.

There were several small classification issues we needed to address, such as to which category a limited liability company formed under a public organisation (such as Triad National Security, LLC) should be assigned, or to which country a start-up that moved but retained an office in its original country should be assigned. We classified a company of the first type as a public organisation in our dataset, and we classified a company of the second type as still 'belonging' to its country of origin.

An additional limitation of this part of our analysis is that we counted individual patents instead of patent families, thereby inflating the apparent prominence of companies with inventions patented in multiple countries. For example, Northrop Grumman has 608 individual active and granted patents in our dataset, while having only 130 patents in the USA, meaning that the actual number of QT inventions emanating from Northrop Grumman is closer to 130 than 608. By contrast, IBM has 286 total individual active and granted patents, with 235 of them in the USA. These ratios might provide further insight into the patenting strategies of the companies for later analysis, but for the analysis at hand this is a limitation which needs to be taken into consideration when assessing the findings.

Out of the 99 top organisations as owners of these individual patents, 40 are established companies, 34 are academic institutions, 15 are QT start-ups, and ten are public organisations. First, we looked at the ratio of patents at the home country to total individual patents worldwide, which we labelled the '*Domestic Patent Quotient*' (DPQ).

$$\textit{Domestic Patent Quotient} = \frac{\#\ of\ patents\ at\ home\ country}{total\ \#\ of\ individual\ patents}$$

The DPQ may be interpreted as a crude indicator of the international commercialisation intentions of a QT organisation, where a low DPQ indicates a strong orientation towards outward-bound patenting activity, and a high DPQ indicates a stronger focus on domestic patenting.

Table 3 International orientation of QT patenting strategy of organisations

	Companies	*Start-ups*	*Public org.*	*Academic org.*
DPQ	0.35	0.40	0.59	0.68
# of patents	3368	949	469	1,471

Table 3 shows that start-ups and established companies exhibit a higher international strategy orientation than public and academic organisations, with academic organisations being the most domestic in their strategies. The differences between China and the USA in the distribution of patents between the four different types of organisations therefore have implications for their relative overall evolving international strategic positions in QT.

4.3 National comparison of patenting behaviour of top QT patenting organisations

Continuing the analysis, we looked at the national distribution of the 99 top QT patenting organisations. The organisations were distributed across 14 countries, but only four countries were home to more than five organisations in the list, namely, China (31), the USA (27), Japan (11), and Korea (9). Combined, these 78 organisations hold 4,927 active individual QT patents.

Table 4 National variations in the organisational mix of QT patents

	China	*USA*	*Japan*	*Korea*
Percentage of QT patents in each country that are domestic patents	87%	43%	44%	36%
Percentage of QT organisations in each country that are academic organisations	58%	19%	0%	44%
Percentage of QT patents in each country belonging to academic organisations	75%	7%	0%	28%

The ratios presented in Table 4 indicate that organisations based in Korea, Japan and the USA have significantly higher outward-oriented patenting activities than those organisations based in China, which mostly obtain domestic Chinese patents. This finding is related to the fact that nearly 75% of the active QT patents in China are held by academic organisations, whereas the equivalent percentage in the other three countries is significantly lower.

As a final analysis to address our second question – namely, who is doing the patenting, and where are they doing it? We constructed a matrix (see Table 5), wherein the row entries represent the number of active individual patents owned by organisations based in a country, and the column entries represent the number of active patents registered in those countries.

Table 5 International source and destination of QT patents

Home countries of patent owners			Countries in which patents are issued						
	China	USA	Japan	Korea	UK	Germany	France	Canada	Total
China	*1,205*	*54*	*17*	*2*	*10*	*11*	*10*	*1*	*1,310*
USA	*68*	*984*	*115*	*51*	*113*	*103*	*92*	*43*	*1,569*
Japan	*16*	*186*	*360*	*3*	*79*	*22*	*21*	*2*	*689*
Korea	*21*	*108*	*13*	*152*	*11*	*9*	*9*	*1*	*324*
UK	*6*	*16*	*11*	*2*	*13*	*10*	*10*	*0*	*68*
Germany	*2*	*6*	*4*	*1*	*5*	*9*	*5*	*0*	*32*
France	*1*	*21*	*4*	*0*	*18*	*16*	*37*	*0*	*97*
Canada	*13*	*189*	*15*	*5*	*15*	*13*	*13*	*17*	*280*
Total	*1,332*	*1,564*	*539*	*216*	*264*	*193*	*197*	*64*	*4,369*

Given that the numbers reported in Table 5 cover only active individual patents held by organisations that are in the list of top 99 QT patenting organisations, they by no means provide an exhaustive map, but several key insights are nevertheless evoked. First, the top patenting organisations in China are overwhelmingly oriented towards patenting in China, whereas the major players outside China are much more international in their patenting strategies. Second, as the number of patents from organisations in a country increases, so does the ratio of their domestic patents to foreign patents. Even the top patenting organisations in the USA have more than half of their active patents at home. Canada (or to be more specific, D-wave systems) is the clear outlier here. Third, if we treat the number of patents obtained in a country as an indicator of expected market value in that country, and also accepting that China has an inflated number of national patents due to patents being owned by academic organisations, it is apparent that the USA is the clear expected early market for these technologies.

5. Discussion

Our analysis of the patent landscape in quantum technologies reveals some notable general trends. First, since the early 2010s the growth pattern in the number of new patents in the field has changed from linear to something approaching exponential, and the trend of patenting activities in quantum computing, quantum cryptography, and quantum sensing, in particular, is rising. One particular reason for this increase is arguably the entrance of China into the QT field, as it seems that the proportion of active QT patents worldwide in China rose from near 0% to about 30% in just one decade; and it is worth noting that there are more than 2,000 QT patents pending in China alone (which is near 50% of the total number of patents pending worldwide in the field).

Secondly, we focused on a comparison of China and the USA, the latter being the historical first mover in the field. This revealed that, although the number of active patents in China outweighs the number in the USA, more than a quarter of active QT patents in China are actually utility models, rather than normal ('invention') patents, and that this ratio is on the rise. Additionally, patents in China possess significantly fewer forward and backward citations, and a lower life-cycle cost attached to them. However, the number of patents pending in China is almost quadruple the number in the USA. Thus, we expect that the number of active QT patents that have China as both the country of origin and the destination is going to increase in coming years relative to the USA. Together with these trends, evidence that the quality of invention patents more generally in China has been rising during recent years additionally suggests that China's emerging role as globally prominent innovator and competitor in the world of QT ought to be taken very seriously by both commercial and government actors in the field.

Finally, we moved to investigate the patenting behaviour of top organisations in the QT field and discovered several interesting facts. First, established companies that have expanded into the domain of QT exhibit the highest tendency towards outward-bound international patenting, while academic organisations exhibit the lowest. Second, although the number of organisations in the set does not vary dramatically between companies (40) and academic organisations (34), companies hold more than twice the number of QT patents as academic organisations. Third, the ratios of the types of organisations holding patents vary greatly between countries, as do the ratios of the types of patenting in which they engage. Fourth, the general geographical patenting propensity of the organisations in our dataset is that as the total number of their QT patents increases the proportion that is devoted to domestic patenting also increases (Canada being the outlier). Finally, our analysis revealed that the QT patenting activity of China is overwhelmingly dominated by Chinese academic institutions. This phenomenon makes it difficult to assess the expected commercial value of the huge number of QT patents emanating from China and requires further analysis into the policy decisions and structural factors that led to China becoming the largest national QT patenting actor in the world in just one decade.

6. Conclusions

In this study, we have utilised a new patent classification tool to analyse the global patent landscape of QT. We have provided a detailed description of how this tool was used, and of our tests of its robustness. Furthermore, we demonstrated that using an AI-enhanced patent classification tool may provide substantial insight into both the technical and industrial/organisational characteristics of an emerging domain of technology and that the outcome may be superior to the outcomes of patent analyses that rely solely on CPC codes and keyword searches that, among other things, result in a high number of false positives. As a demonstration of the practical advantages of employing AI-enhanced patent analysis for emerging technological industries, the following insights about the field of QT have been generated: QT is emerging rapidly as a field of technology with substantial industrial and commercial interest (not just academic interest), particularly in the sub-fields of quantum sensing, quantum computing, and quantum cryptography; and, China has a significant and growing presence in the field, as already noted in the literature (Olijnyk, 2018; Sharma, 2018), and is likely to be a major player in the future. However, our research has also indicated that the potential for the emergence of a substantial commercial market for QT – open to international competition – is likely to be seen first of all in the USA, based on the patenting activities of the top QT patenting organisations worldwide.

These findings may guide both private and public actors in the field of QT, and lead to re-alignment of patenting strategies. The findings also evoke several questions for further analysis, including how the various sub-fields of QT and their technological evolution are intertwined; how the core QT technologies are related to complementary technologies; what methods may be available to accurately distinguish and characterise patents from different sub-fields of QT; and, finally, what predictions may plausibly be made regarding future developments in the broad domain of QT based on analysis of previous and current trends in QT patenting activities.

In short, in this paper we have demonstrated how the sophisticated use of intellectual property information, enhanced by the artful deployment of AI techniques, may produce more reliable and useful insights for policy makers and managers about global technological innovation in specific fields than is possible through conventional methods of data collection and analysis.

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Notes

1. The actual verified count, as of 12 November 2020, was 14,425 QT patent families worldwide.
2. Search query = (‘quantum dot’ OR ‘quantum dots’ OR ‘quantum-dot’) AND display.
3. We analysed the top 99 QT patent owning organisations rather than the top 100 because the Cipher software groups the patent applications of individuals under the generic label ‘Private Owner’ and which, when aggregated, technically counts as the ‘top’ organisation. We therefore excluded the ‘private owner’ category.
4. Cipher has an in-built scoring system for calibrating the strength of a classifier, on a scale of 0.0 to 1.0, with a higher score indicating greater accuracy in matching the identified patent to the AI-defined field.

Appendix

Methodology for employing AI to generate an operational definition of QT for constructing a robust global QT patent dataset.

A1 The dataset

A1.1 The patent data: basic features and issues

Our QT dataset was built using *Cipher*, which is a commercially available online patent information service developed by Aistemos Limited (2020) which enables the creation of trained AI classifiers to tag patents against pre-defined technological domains, with the training of the models based on data generated endogenously from the patent records themselves. According to a published study by a team from *Aistemos*, a combination of domain specific normalisation and transformations, and a separately trained patent-specific language model, are used to produce textual and metadata embeddings for the training of models in *Cipher*, and model parameters are obtained through either random or directed hyperparameter searches (Harris et al., 2020). The *Cipher* data base is comprehensive, including data from entire patent families worldwide, and covering both granted patents and published patent applications, which may be searched independently. All training models in *Cipher* utilise information from the title, abstract,

citations, CPC codes, and claims of the patent files, but not from the description section of the documents (Malek, 2020). When using Cipher's machine-learning platform it is typically necessary to perform a large number of iterations in the training process to generate representative results (Harris et al., 2020).

To form our QT classification tool ('classifier'), we started with a sample training dataset on 'quantum computing' provided by *Aistemos* and customised it to delete any patents that were clearly unrelated to quantum technologies (e.g., which contained the keyword 'quantum' but obviously contained nothing pertinent to QT), and other patents which consisted mainly of cryptographic schemes 'against' quantum computers (anti-quantum or quantum-resistant schemes). Following this initial filtering exercise, we proceeded to iteratively construct a robust QT classifier by repeatedly refining the training set using the machine-learning tools of the program, verifying the results manually at each step based upon their consonance with the generally accepted scope of the QT field as characterised in the pertinent published literature (Dowling and Milburn, 2003b; Riedel et al., 2019). In short, using the *Cipher* database and software platform, we built an AI-based operational definition (i.e., a 'classifier') of the field of QT using a combination of machine-learning tools and human judgement guided by both the AI and accepted understandings of the technology as promulgated in the pertinent literature.

We faced several issues regarding the construction of a new QT classifier using machine learning techniques:

- As the size of the training set grew larger, re-running the classifier became problematic; leading us to stop the training process at 11,600 patents (5,220 positives and 6,380 negatives). The typical recommended size of a robust the training set is around 750 (250 positives and 500 negatives), but drawing the lines on what can be considered as part of QT and what is not, required further clarification. We did not want the classifier to miss an essential sub-field of the technology just because it did not have enough patents in the training set related to that particular category of technologies.
- Most of the initial patents were selected by hand, following different keyword searches, which meant that the training set contained some internal biases. For example, we tried to include the use cases of quantum dots for sensing and computing purposes while not covering uses such as 'quantum dot based printer ink'.
- One of the main differences between using a trained classifier based on machine learning and keyword searches combined with CPC codes is that for the training set it is necessary to provide not only what 'is' part of quantum technologies but also what 'is not.' In this sense, we believe, depending on the negatives for the training set, a variety of valid classifiers may be constructed, with each focusing on different aspects of QT, and ours is only one example of that wider class.
- Finally, we encountered some grey areas, requiring human judgement, when it came to deciding whether or not certain patent applications should be considered as part of QT. For example, an electronic control system that is designed to be used for registering readouts from a superconducting quantum circuit was accepted as part of QT for the purposes of this study, even though it might plausibly be classified as belonging to a classical system.

Due to the limitations listed above, it is of course possible that a better classifier than ours could be constructed using the same supervised machine learning techniques. Nevertheless, as demonstrated in this paper, the current classifier utilised in this study outperforms analyses conducted using only keyword searches and CPC/IPC codes. Thus, even though our final patent set is non-exhaustive, it is still an accurate and sufficiently large enough sample size to correctly describe the global patent landscape of quantum technologies.

A1.2 Building the dataset and testing its robustness

Initially we tested our classifier by comparing its results with the results of a keyword search provided in literature (Winiarczyk et al., 2013) which is replicated below in Boolean form:

> "quantum computer' OR 'quantum computing' OR 'quantum computation' OR 'quantum compute' OR 'quantum communication' OR 'quantum information' OR 'quantum bit' OR qubit OR qubit OR ('quantum' AND 'random number generator') OR 'quantum cryptography' OR ('quantum key' AND (distribut* OR exchang*)) OR 'quantum Fourier' OR ((quantum OR photo* OR optic*) AND BB84) OR (quantum AND grover) OR (quantum AND ('single photon source' OR 'single-photon source' OR 'single photon generator' OR 'single- photon generator' OR 'single photon detector')) OR (quantum AND spintronic*)."

Out of 4,273 patent families in the dataset generated by the above keyword search, our classifier identified 3,772 patent families above *Cipher's* 0.5 threshold and 3,700 patent families above *Cipher's* 0.7 thresholds for the strength of the patent-classifier-patent fit.[4] We checked the 72 patents that fell between the 0.5–0.7 score by hand, and although half of them definitely belonged to the set of QT (such as single photon sources or quantum cryptographic methods) half of them did not. For example, a patent titled 'A photon source' containing the sentence 'The source may be configured as a single photon source by incorporating quantum dots' was found, which indicates that in its current form and proposition, it is not a single photon source. To root out false positives at the expense of some true positives, we set the threshold as 0.7 for the rest of the study.

We then tested our classifier again by comparing its results with the results obtained by applying an experimental *Cipher* classifier produced by *Aistemos* for the field of 'quantum computing' which contained 4,104 patent families. When we applied our classifier to that reference dataset we obtained 3,721 patent families that satisfied the threshold fit requirement of at least 0.7. Our classifier identified 164 of the 4,104 patent families as falling within the 0.0–0.1 threshold range. Examples of the 'false positives' in the reference dataset included patents with the following titles (plus our explanation of the actual subject matter of the patent):

- 'A kind of quantum wine' (recipe for an actual wine for 'raising sleep quality').
- 'A kind of control system of multi-functional quantum hair tonic comb' (a comb with herbaceous plant essence for nourishing hair and massaging the head).
- 'A kind of quantum generation converting apparatus' (a cup for drinking tea with a leak hole for honey or granulated sugar to be leaked directly into the cup).

To conduct a third round of testing of our QT classifier we built a completely new dataset by casting a wide net to cover as many patents as possible, using a combination of keyword searching and other methods and sources. We commenced with the following broad-scope Boolean search, which contained some redundancies, since it was constructed by combining searches with a selection of keywords drawn from a wide variety of sources, and generated an initial list of around 1.6 million patent families:

> "quantum computer' OR 'quantum computing' OR 'quantum computation' OR 'quantum compute' OR 'quantum communication' OR 'quantum information' OR 'quantum bit' OR qubit OR qbit OR ('quantum' AND 'random number generator') OR 'quantum cryptography' OR ('quantum key' AND (distribut* OR exchang*)) OR 'quantum Fourier' OR ((quantum OR photo* OR optic*) AND BB84) OR (quantum AND grover) OR (quantum AND ('single photon source' OR 'single-photon source' OR 'single photon generator' OR 'single- photon generator' OR 'single photon detector')) OR (quantum AND spintronic*) OR teleportation OR qkd OR qubit* OR 'single photon' OR 'single-photon' OR spintronic* OR entanglement OR qbit* OR entangled OR (gravity AND sens*) OR gravito* OR magnetome* OR nano* OR quantum OR 'quantum simulation' OR 'quantum imaging' OR 'quantum sensing' OR 'quantum sensor' OR 'quantum computation' OR 'quantum computing' OR 'quantum computer' OR 'quantum coding' OR 'quantum programming' OR 'quantum error correction' OR 'quantum error correcting' OR 'quantum circuits' OR 'quantum algorithm' OR 'quantum algorithms' OR 'quantum network' OR 'quantum networks' OR 'quantum channel' OR 'quantum channels' OR 'quantum cryptology' OR 'quantum cryptography' OR 'quantum key' OR 'quantum teleportation' OR 'quantum information' OR 'quantum technology' OR 'quantum technologies' OR semicond* OR supercond*."

In addition to this keyword search, we used *Cipher's* in-built academic patent set covering 151 institutions (mostly universities), which identified around 660,000 patent families. Finally, we added patent families from an additional 278 organisations, by hand, using *Cipher's* suggestion algorithm for organisations with similar portfolios. In total, by combining these three procedures we built a dataset of over 4 million patent families. We then ran our QT classifier against our large manually constructed dataset, using a 0.7 fit threshold, and determined that just 12,149 of the over 4 million patent families in the set actually qualified as belonging to QT according to our classifier. Following that test we then ran our QT classifier against the whole population of all patents, in all technological fields, worldwide (accessible via the platform), using the same 0.7 fit threshold, and determined that 14,425 of all patent families globally could be classified as referring to genuine QT inventions according to our QT classifier (correct as of 12 November 2020). Given that the order of magnitude of the results achieved using our QT classifier against the whole population of patent families worldwide was similar to what we obtained through manual efforts, we decided to use the dataset generated using the AI tools of *Cipher* as the basis for our subsequent analysis of the field.

Finally, the strength of our QT classifier according to the *Cipher* system registered an extraordinarily high score of almost 98% (0.976), which means that we expect and accept an error of between 2% and 3% (around 350 patents) in the form of 'false positives' within the dataset. Table A1 contains the detailed results of the test for the classifier strength.

Table A1 Robustness test for the QT classifier, using cipher algorithm

Test no.	*True positive*	*True negative*	*False positive*	*False negative*	*Precision*	*Recall*
1	1,705	2,059	68	35	0.962	0.98
2	1,698	2,043	84	42	0.953	0.976
3	1,691	2,058	69	48	0.961	0.972
Mean	1,7	2,050	73.7	41.7	0.958	0.976

The precision and recall of the classifier are defined as below, and the classifier strength is given as the mean of the arithmetic average of these two quantities over many repetitions:

$$\text{Precision} = \frac{TP}{TP+FP}, \text{Recall} = \frac{TP}{TP+FP}$$

Following this first robustness test, we tested our QT classifier again, by running it against three independently developed quantum-related datasets from the *Cipher* repository, based on experimental quantum classifiers with a more limited scope. The results, shown in Table A2, in which a high proportion of the patent families in the three comparison datasets are verified as true positives, confirms the robustness of our QT classifier.

Table A2 Robustness tests against three experimental classifiers

Dataset topic – title	*A. No. of purported quantum patent families in comparison dataset*	*B. No. of true positives confirmed by QT classifier*	Ratio B/A
Quantum computation	334	325	0.97
Quantum communication	124	114	0.92
Quantum computation	291	284	0.98

Additionally, we tested our QT classifier against patent datasets we constructed in several specific sub-fields of QT using the dominant approach to patent analytics found in the literature, which is to search for patents of interest using CPC codes and specific keywords. Since there are no curated datasets available for the topics of quantum sensing and quantum simulation, and because the choice of appropriate keywords was not obvious, we omitted searches regarding those two subfields. It should be noted, for example, that keyword searches such as ‘quantum sensor’ reveal a significant number of false positives since phrases like ‘light quantum sensor’ are widely used for non-quantum type of sensors, and hence utilisation of specific searches on quantum sensing devices is not reliable. We therefore restricted ourselves to constructing new datasets for QT sub-fields in the following four areas: quantum cryptography, quantum computers, quantum communication, and quantum key distribution. The results presented in Table A3 demonstrate that our QT classifier is well-suited to identifying most of the patents in these four sub-fields defined according to CPC codes and commonly used keywords.

Table A3 Robustness tests against four QT sub-field databases

CPC code (and keyword)	A. No. of purported quantum patent families in comparison dataset	B. No. of true positives confirmed by QT classifier	Ratio B/A
H04L9/0852: quantum cryptography	1,792	1,491	0.83
G06N10/00: quantum computers	2,258	1,924	0.85
H04B10/00: (communication) + quantum	88	75	0.85
'Quantum key distribution'	1,251	1,227	0.98

Table A4 Robustness tests against results of 2018 European Commission Study

Search query	*Hits (2018)*	*True positives (manual check – previous study)*	*Hits (2020)*	*True positives (our classifier)*
(photon OR photons OR photonic) AND (entangled OR entanglement OR entangling OR entangle)	337	333	475	438
cpc_code: 'G06N99/002' OR (((qbit') OR ('qbits') OR ('qubit') OR ('qubits')) OR (('quantum computer') OR ('quantum computers')) OR (('quantum computation') OR ('quantum computations')) OR (('quantum memory') or ('quantum memories')) OR ('quantum error correction') OR (('quantum simulation') OR ('quantum simulations')))	1,373	1,149	1,630	1,342
cpc_code: 'H04L9/0852' OR cpc_code: 'H04L9/0855' OR cpc_code: 'H04L9/0858' OR (quantum AND key AND distribution) OR (qkd) OR (quantum AND cryptography)	1,338	1,161	3,272	2,782
(spin OR spins) AND (entangled OR entanglement OR entangling OR entangle)	104	24	129	29
('cold atom') OR ((atom OR atoms OR atomic) AND (interferometer OR interferometry))	263	150	391	28

As a final test of the robustness of our QT classifier's ability to identify genuine QT patents, we repeated several keyword searches that were employed in a previous study conducted by the European Commission (Travagnin, 2019), using the Global Patent Index database of the European Patent Office, in which the 'title and abstract (and in case of doubts the entire text with its claims)' were read for each patent application to filter out false positives, thereby identifying 'true positives' with high precision. We then ran our QT classifier against the datasets that we built using those same search terms. The results are presented in Table A4.

The results presented in Table A4 reveal that, on the whole, our QT classifier performs robustly, with a level of precision that is arguably greater than for QT analyses that rely solely on keywords and CPC codes. However, while this may hold true for the dominant fields of QT – namely quantum computation simulation, quantum communication/cryptography, and quantum metrology/sensing – the results appear problematic for cold-atom based applications. This is because these sub-fields of QT were not explicitly included in the classifier when it was built. This should also be noted as a limitation of our dataset. Nevertheless, we may conclude from the results of the robustness tests reported in Tables A1, A2, A3 and A4 that the overall approach of using an AI-based platform for classifying and identifying appropriate technology, and for constructing an instrument for analysing pertinent patents, is a powerful tool for accurately characterising the domain of QT.

Book Chapter 1.3: Subchapter 7.2.2: Milestones of research activity in quantum computing[85]

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We argue that QC underwent an inflection point circa 2017, when long-promised funding materialised, which prompted public and private investments around the world. Techniques from machine learning suddenly influenced central aspects of the field. On one hand, machine learning was used to emulate quantum systems. On the other hand, quantum algorithms became viewed as a new type of machine learning model (creating the new model of variational quantum computation). Here, we sketch some milestones which have lead to this inflection point. We argue that the next inflection point will occur around when practical problems are first solved by quantum computers. We anticipate that by 2050 this will have become commonplace, while the world will still be adjusting to the possibilities brought by quantum computers.

7.2.2.1 General overview

What is quantum computing?

Today's computers which we know and love—whether smartphones or the mainframes behind the Internet are all built from billions of transistors. (A transistor is an electrically controlled switch which is ultimately the power behind any electronics.) While transistors utilize quantum mechanical effects (such as tunneling, in which an electron can both penetrate and bounce off an energy barrier concurrently), the composite operation of today's computers is purely deterministic or classical. By classical, we mean classical mechanics, which is exactly the physics (also known as mechanics) that we would anticipate day to day in our lives. Quantum computers are not intended to always replace classical computers. Instead, they are expected to be a different tool to complement certain types of calculations. We will elaborate shortly.

The term quantum mechanics (in German, quantenmechanik) dates to 1925 in work by Born and Jordan [48] and comprises the physics governing atomic systems. Quantum mechanics contains principles and rules that appear to contradict the classical mechanics we are so intuitively familiar with. Such counterintuitive phenomena provide new possibilities to store and manipulate (quantum) information. This is exactly what a quantum computer should do. The information must be stored and processed in the matter. You can think of a quantum computer as providing new mechanisms to store, process, and generally manipulate data. Indeed, the ultimate limitation of computational power is given by quantum physics.

[85] https://iopscience.iop.org/book/oa-edit/978-0-7503-6342-6/chapter/bk978-0-7503-6342-6ch7

How did quantum computing begin?

QC dates back at least to 1979, when the young physicist Paul Benioff [49] at Argonne National Laboratory in the US proposed a quantum mechanical model of computation. Richard Feynman [50] and independently Yuri Manin [51] suggested that a quantum computer had the potential to simulate physical processes that a classical computer could not. Such ideas were further formulated and developed in the work of Oxford's David Deutsch [52], who formulated a quantum Turing machine and applied a sort of anthropic principle to the plausible computations allowed by the laws of physics. What we now call the Church-Turing-Deutsch principle asserts that a universal (quantum) computing device can simulate any physical process. (This hypothesis does not give an algorithm but just provides an assertion that such an algorithm exists.) Yet even the most elementary quantum systems appear impossible to fully emulate using classical computers, whereas quantum computers would readily emulate other quantum systems [50, 63].

Early insights into the computational power of quantum computers were based on the assertion that it is impossible to develop an efficient classical algorithm able to accurately emulate quantum systems [50, 53]. While this claim has not been formally proven, ample empirical evidence supports it. Yet there are many computational problems where the required computational resources are better understood than simulating physics. These problems arise in the form of, for example, the theory of numbers, groups, or properties of graphs. For decades a small number of researchers worked to understand if one might expect an exponential quantum speedup for problems long studied in computer science. The early algorithms, such as Deutsch-Jozsa [54] and Simon's [55] solved elegantly contrived problems, making prima facie practical merit difficult to envision.

A more practical breakthrough occurred in 1994 when Peter Shor proposed an efficient quantum algorithm for factoring integers. This would open the door to decrypt RSA-secured communications [56]. Shor's algorithm, if executed on a quantum computer, would require exponentially less time than the best-known classical factoring algorithms. Other seminal early findings include Grover's 1996 quantum algorithm [57], which can search through N items in a database in $\sqrt{N}$ steps. It turns out that Grover's algorithm is provably optimal: It is not possible for a quantum computer to search N unstructured elements any faster than $\sqrt{N}$ steps [58], which could be significant in practice. Can these and other quantum algorithms (see table 7.1) be realized experimentally [59]?

7.2.2.2 Where is quantum computing heading?

As of today, billions of dollars of public and private investment are being spent to build quantum computers [68]. In October 2019, Google, in partnership with NASA, performed a quantum sampling task that appears infeasible on any classical computer [69]. Late in 2020, Chinese scientists [70] reported results of like significance. At the core of these developments is the quantum mechanical bit: the qubit, as first coined by Benjamin Schumacher [71], who asserts that the term arose out of a 1996 conversation with William Wootters (for qubit, see table 7.2). Simply, a qubit is a two-state (binary) quantum system.

Table 7.1. Expected quantum complexity. Theory predicts that quantum computers have the potential to rapidly execute several important algorithmic tasks. Originally developed for the gate model, variational counterparts to Grover's search [61], optimisation (QAOA [62]), linear [63] (and nonlinear [64]) systems, and quantum simulation (VQE, first proposed in [65] and first demonstrated in [66]) have been developed. Factorization and discrete log can readily be mapped to Ising optimisation problems, yet the scaling remains unclear. Polynomial time variational quantum factoring might instead be accomplished by means of the circuit to variational algorithm mapping [67].

Problem class	Quantum complexity
Factorization	Polynomial [56]
Discrete log	Polynomial [56]
Complete search	$\mathcal{O}(\sqrt{N})$ [57]
Sparse linear system	Polynomial [60]
Quantum simulation	Polynomial [53]

Table 7.2. A brief comparison of traditional bits and quantum bits (qubits).

The quantum bit or qubit
A traditional computer operates using bits, 0 and 1. Each classical register or classical memory must be in a single classical state, which is represented by a string of bits (e.g., 0011 or 0100000111). Quantum computers allow quantum registers and memories to be in multiple states concurrently. For this reason, quantum computers are often described as enabling parallel processing.

There are a variety of physical approaches to creating qubits. For example, a single photon of light can represent two quantum states given by vertical and horizontal polarization. Common qubit realisations include superconducting electronics [69], trapped ions [72], and various optical realisations [73]. Qubits are the building blocks of fully programmable (e.g., universal) quantum computers. The universal quantum Turing machine's abstraction from physics makes it harder to realize; consequently, this model has fallen from interest [49].

Qubits should be isolated from their surroundings yet also be made to interact. Quantum algorithms are described by quantum circuits; such circuits depict actions on and interactions between qubits by quantum gates and encompass today's de facto universal model of quantum computation. In practice, design imperfections and random noise can not be avoided, meaning that the ideal qubit can never exist. Such noise processes serve to restrict quantum circuit depth. Over the last several decades researchers have developed a powerful theory of quantum error correction,proving that qubits need not be perfect to realise high-depth quantum circuits [74]. Indeed, quantum error correction proves that a small amount of noise can be tolerated: called the error tolerance threshold [75]. Hence, according to the laws of physics, nothing

fundamentally prevents humans from building a quantum processor capable of executing high-depth quantum circuits.

A universal quantum computer is assumed to be error tolerant through error correction [76, 77]. Throughout the history of quantum computation, several universal models of quantum computation have been developed and shown to be computationally equivalent to the *de facto* quantum circuit model [74]. This includes adiabatic quantum computation [78, 79] both discrete and continuous quantum walks [80, 81], measurement-based quantum computation [82] as well as one of the authors installment proving universality of the variational model [67].

Assuming this idealized (universal) setting, several miraculous quantum algorithms have been developed which would offer an advantage over the best-known classical algorithms. Lower bounding the computational resources required in quantum (and classical) algorithms has, however, proven extremely difficult. How might we rule out the existence of a better algorithm when the computational power of the class of possible algorithms is not fully understood?

For example, regarding recent quantum adversarial advantage demonstrations [68, 70], who is to say that a classical algorithm will not one day be discovered which can replicate the reported sampling task(s)? This does not imply that such assumptions are not without formal footing. Elegant methods exist to compare the power of a classical computer to the power of a quantum computer [83]. It does, however, make the timeline for a practically meaningful quantum computation difficult to predict. So with all of the dramatic progress, what might we expect from NISQ era quantum processors [84]?

7.2.2.3 Design constraints

Design constraints limit manufacturing qubits. Working with current design constraints means that we must find ways to utilize imperfect qubits. The question is whether we can still build meaningful systems with imperfect devices.

Despite outperforming classical computers at an adversarial advantage [69, 70], such a demonstration was tailored to favor quantum processors and has unclear practical applications. Even with Moore's law failing [85], traditional computing resources are ever improving and increasingly accessible. Moreover, the von Neumann architecture has a first-mover advantage: The entire tool chain, the compilers, algorithms, and so on that are in use today are tailored for this architecture. To instead utilize quantum systems as a computational paradigm represents a dramatic change in how problems must be decomposed, encoded, and compiled and in how we think about computing. Perhaps gleaning lessons from sampling [69, 70], we must learn to look towards problems that are more amenable to quantum processors, with desirable criteria such as the following:

1. Problems which bootstrap physical properties of a quantum processor to reduce implementation overhead(s).

2. Systems and/or models of computation which offer some inherent tolerance to noise and/or systematic faults.

3. Problems which utilize the ability of quantum systems to efficiently represent quantum states of matter, called the memory *scaling argument* (see table 7.3).

Table 7.3. The memory scaling argument asserts that even the worlds largest computer cannot store into its memory any but the simplest quantum states.

The memory scaling argument asserts that quantum states exist which cannot be stored using even the largest classical memories. Early arguments for the quantum computing advantage considered an ideal state of interacting qubits, requiring about 2^{n+1}. 16 bytes of information to store assuming 32-bit precision. This reaches 80 terabytes (TB) at just less than 43 qubits and 2.2 petabytes (PB) at just under 47, for example, the world's largest memory of the supercomputer Trinity. Hence, applications with ≥47 qubits might already outperform classical computers at certain tasks. While this argument did not account for noise and approximation/compression schemes to reduce required memory, similar arguments are considered valid lines of reasoning today.

These constraints have led us to what is now called the variational model of quantum computation. In the absence of error correction, NISQ era quantum computation is focused on quantum circuits that are short enough and with gate fidelity high enough that these short quantum circuits can be executed without quantum error correction, as in the recent quantum supremacy experiments [69, 70]. Herein lies the heart of the variational model: by adjusting parameters in an otherwise fixed quantum circuit, low-depth noisy quantum circuits are pushed to their ultimate use case.

NISQ circuits typically bootstrap experimentally desirable regularities inline with criterion 1: The gate sequence itself is fixed, while the gate angles can be varied. A classical computer will adjust parameters of a circuit. Measurements will be used to calculate a cost function, and the process will be iterate (see table 7.4 for some examples).

The prospects of the variational model are limited by the computational overhead of outer-loop optimisation. This requires significant classical computing resources. Variational model proposes some alternatives to this. (For a further comparison of these models, see table 7.5.)

7.2.2.4 How did quantum computing develop prior to 2017?

A turning point in the development of quantum computation appears around 2017. At this point, several long-promised large funding programs began, such as the European Quantum Flagship and the American National Quantum Initiative Act (which happened around the world and was in the billions of US dollars). Most national investments appear to keep a country competitive in technological development. There are many initiatives around the world, adding up to more than 20 billion USD committed in public funding. Many private companies also invested dramatically around this time.

Table 7.4. Hamiltonian complexity micro zoo. Anticipated computational resources to determine ground state energy and calculate energy relative to a state. Restricted Ising denotes problems known to be in P. An asterisk denotes expected and not formally proven conjectures. Electronic structure problem instances have constant maximum size and so are assumed to be in BQP, whereas the ZZXX model admits a QMA-complete ground state energy decision problem.

Problem Hamiltonian	Finding ground energy (classical/ quantum)	Calculating state energy (classical/ quantum)
1-Local Hamiltonian	Polynomial	Polynomial
2-Local ising	*Exp	Polynomial
Electronic structure	*Exp	*Exp/Polynomial
structure ZZXX model	*Exp	*Exp/Polynomial

Table 7.5. Comparison of standard gate model quantum computation versus variational quantum computation. Variational quantum computation trains short quantum circuits to reach their maximum use case yet requires significant classical coprocessing to train these quantum circuits.

Variational	Traditional
• Agnostic to systematic errors • Tightly connects hardware with software to overcome hardware constraints • Optimizes short depth circuits for optimal use • Emulates Hamiltonians by local measurements • Outer loop optimization can require significant classical computing resources • Coherence time and error rates limit circuit depth	• Intuitive and familiar, textbook quantum algorithms adhere to the circuit model • Theoretical analysis, including complexity, has largely been proven possible • Impossible to execute all but the shortest circuits (smallest examples) with current hardware • Ignores hardware constraints and susceptible to both systematic and random errors

Meanwhile, quantum computation was merged with machine learning in two different ways (see [86]). First, quantum circuits can be trained variationally. In other words, quantum circuits can be viewed as machine learning models. Second, machine learning can be applied to a host of

problems faced in building and emulating quantum systems. These two facts encouraged the tech industry to participate in QC research and development. (In fact, a new model of computation was developed and proven to be universal [67].)
While those working in the field might readily agree that things have rapidly developed since around 2017, putting data behind this claim is the focus of this section. Hence, we will quantitatively describe the levels of activity before 2017, especially focusing on the field of quantum algorithms.

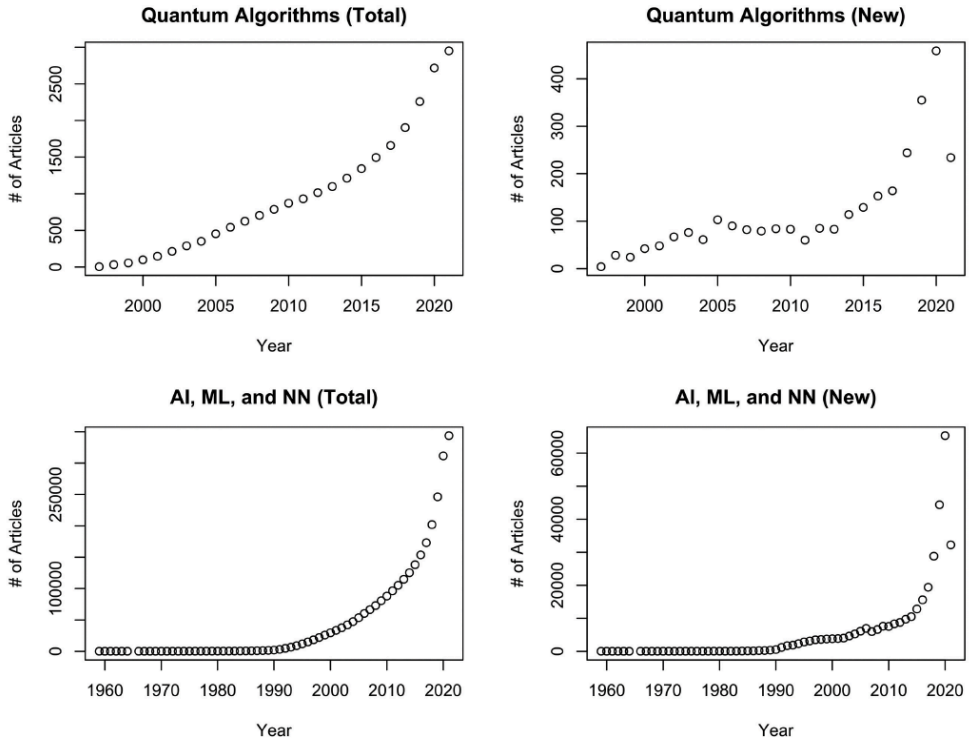


Figure 7.3. The numbers of new and total published articles in the quantum algorithm and artificial intelligence fields.

We have utilized two data sources for this section, one for academic publications and one for patent publications: Web of Science owned by Clarivate Analytics PLC and the Cipher platform owned by Aistemos Ltd. However, our readers can use the same queries[86] to reproduce our results. To generate our queries, we have used the previous ones created by previous publications in the literature [87, 88], and personal expertise.

[86] For quantum software and algorithms: (('quantum machine learning') OR ('qml' AND 'quantum') OR ('quantum approximate optimization') OR ('vqe' AND 'quantum') OR ('variational quantum eigen*') OR (quantum algorithm*") OR ('quantum software') OR ('quantum Machine Learning') OR ('Classical-quantum Hybrid Algorithm*) OR ('quantum PCA') OR ("quantum SVM') OR ('variational Circuit* AND 'quantum') OR ("quantum Anneal* AND 'algorithm*") OR (quantum Enhanced Kernel Method*") OR ('quantum Deep Learning') OR (quantum Matrix Inversion') OR ("quantum embed*') OR ('quantum neural') OR ('quantum perceptron') OR ('quantum tensor network*')) For artificial intelligence: ('machine learning') OR ('artificial intelligence') OR ('neural network*)) Date: 11 June 11 2021.

To build our study, we first consider figure 7.3. We see in the upper left-hand panel the growth of quantum algorithms articles. We see what appears to be an increase between 2015 and 2020. By total, we mean the entire sum up until that point. By new, we mean the number of articles in a given year. In the left top panel of 7.3, we again see a jump between 2015 and 2020.

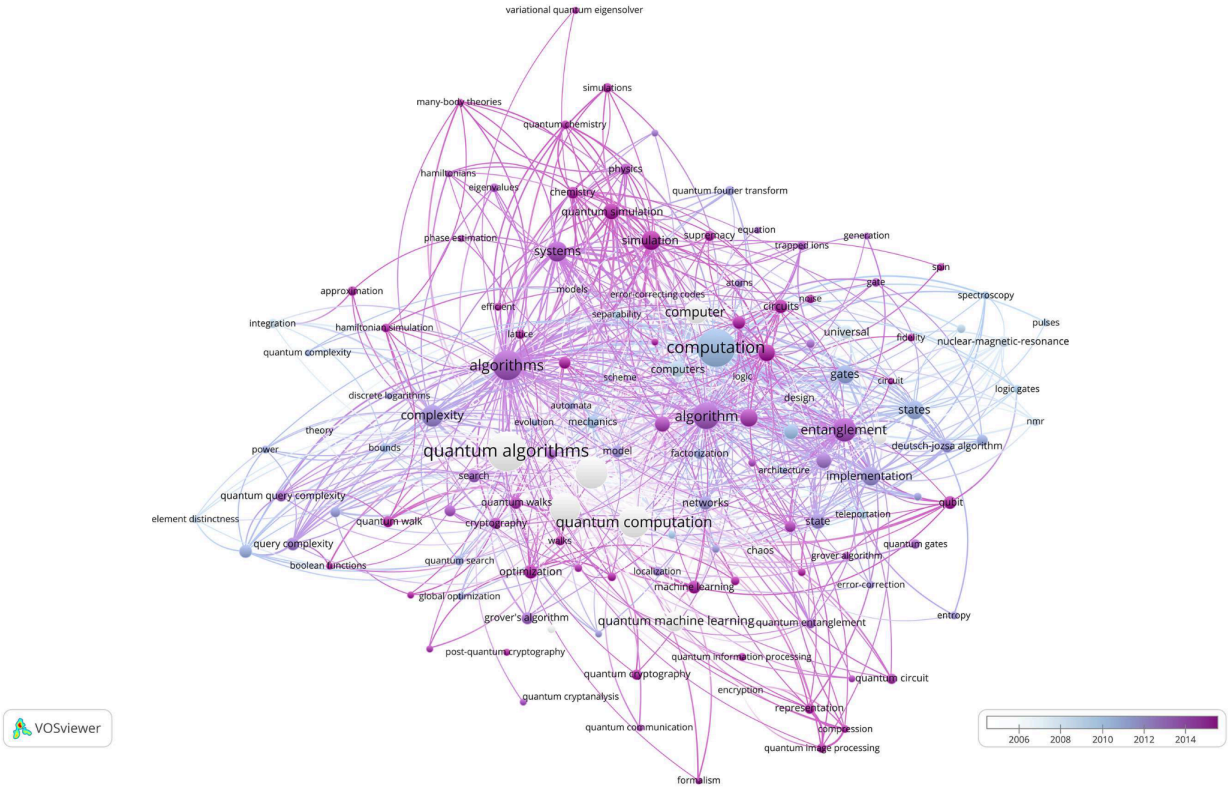


Figure 7.4. Overlay visualization of author keywords used in academic articles in time.

Additionally, we ran the publication dataset through a software tool for constructing and visualizing bibliometric networks (VOSViewer) [89] to run author figure keyword clustering, which resulted in figure 7.4. In this figure, each node represents an author keyword, the size of the node is correlated with how many times the keyword appears in the dataset, connections between nodes represent co-occurrences of those keywords, and the color scale represents the average year of the keyword in the literature.

Here, one can notice the following point. Keywords such as *quantum algorithms*, *quantum computation*, and quantum computer are mainly the keywords utilized by older literature. In recent years they have been replaced with more field specific terms such as *quantum chemistry, variational quantum eigensolver*, and *quantum image processing*. This indicates an evolution of the literature into partially distinct lines of research, which are more developed topics in terms of maturity, compared to earlier keywords utilized in the literature.

We ran a similar analysis for the collaboration between countries (figure 7.5). The country-level data are associated with the affiliations of authors, and this map represents only the academic literature created by cross-country collaboration. This visual reveals that, although countries such as England, Germany, China, and the US are located in the centre of the collaboration network, a considerable number of new countries joined this network in recent years (represented by dark purple in the figure).

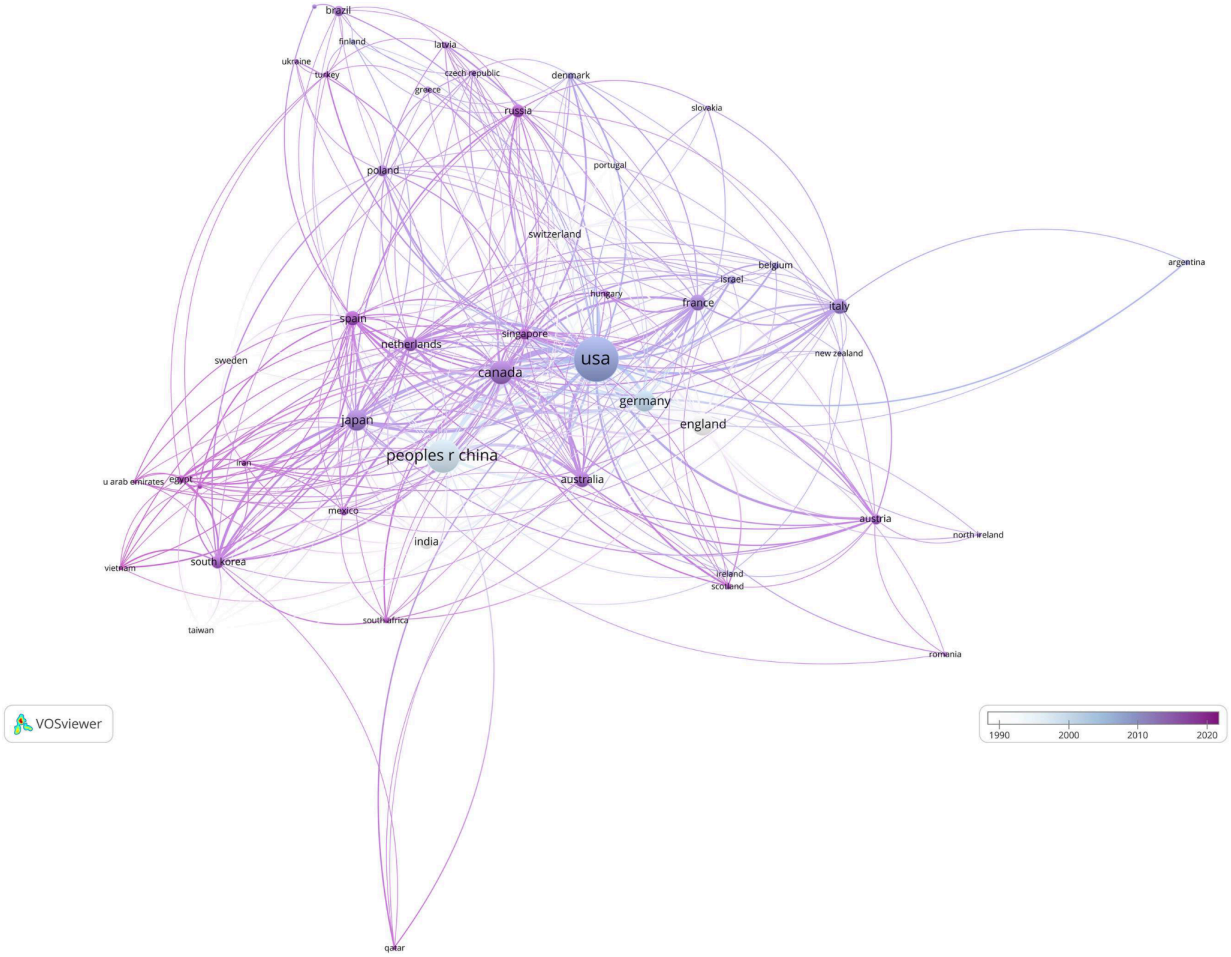


Figure 7.5. Overlay visualization of countries of origin of academic articles in time.

In terms of numbers, the patent literature reveals results similar to those of academic publications. We see a rise in the early 2000s in the top left panel in figure 7.6. We again see a jump before 2020. That sharp jump is the turning point we are discussing. The new and total numbers reflect this. We see similar jumps in the AI fields at a much larger scale (bottom two panels). When we compare the trends in figure 7.6 with those in figure 7.3, it is clear that scientific interest in both fields has been steadier than commercial interest until around 2016-17, and then both show a strongly upward trend.

This exploration of the academic and patent landscapes reveals several important insights into the current state of the field. First of all, comparison between AI and QC in terms of

commercialization is clearly an overstatement in terms of patents. Using the queries given, we were able to find 122 609 patent families in the AI field versus 144 in quantum algorithms. Similarly, there were 343 808 articles in AI and 2951 in quantum algorithms. These represent differences of two to three orders of magnitude in publications and patents between these fields. In this sense, quantum algorithms can be related to the early 1990s when compared to AI, which might provide some insight into how the algorithms and QC might evolve in the coming decades.

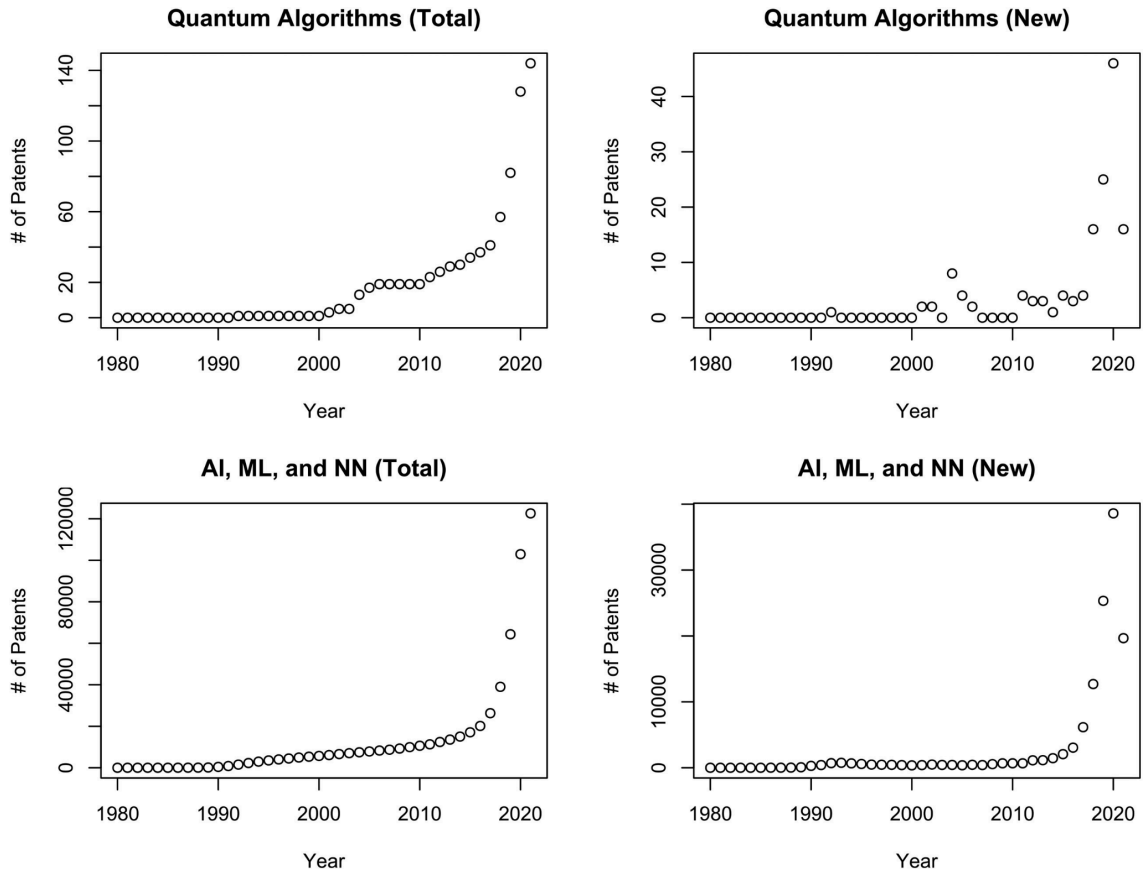


Figure 7.6. The numbers of new and total patents in the quantum algorithm and artificial intelligence fields.

Finally, to see how this activity has been translating in the entrepreneurial realm, we gathered a list of companies[87] in QT and identified the startups related to QC in them to compare them in figure 7.7. It should be noted that other fields under QT (such as quantum sensing and quantum communication/cryptography) have also been gaining popularity in the recent years. From the figure, we can see that startups in QC are a relatively new phenomenon compared to companies in QT, but both have been rapidly increasing in number during the last five years.

[87] This list was collected by us manually and contained 439 companies as of June 2021. We used open access resources such as Crunchbase, LinkedIn, The Quantum Insider, and Quantum Computing Report

In summary, some historical differences and similarities between these fields can be seen in figures 7.3 and 7.6. One clear difference is of the scales, as there are orders of magnitude between the fields. The second difference is that since early 1990 there has been a steady increase in the total number of patents obtained in the field of AI compared to the almost zero activity in the field of quantum algorithms except a brief and short-lived interest in the mid-2000s. One clear similarity is the sudden spike in the late 2010s, especially after 2016-17, which is also evident in figure 7.7. This can be attributed to long-promised funding materialising, which prompted public and private investments around the world. The origins of some of the public funding schemes can be attributed to fear of missing out for countries with existing scientific investments in the field (figure 7.5). Some can be explained by public demonstrations of IBM's and Google's superconducting quantum processors, signaling to the public (and investors) that QC is coming into the realm of calculable risk from Knightian uncertainty [90]. Regardless of the specifics, it is clear that both the number of new academic articles and new patents per year and the number of startups in QC have increased significantly, starting from 2016 to 2017.

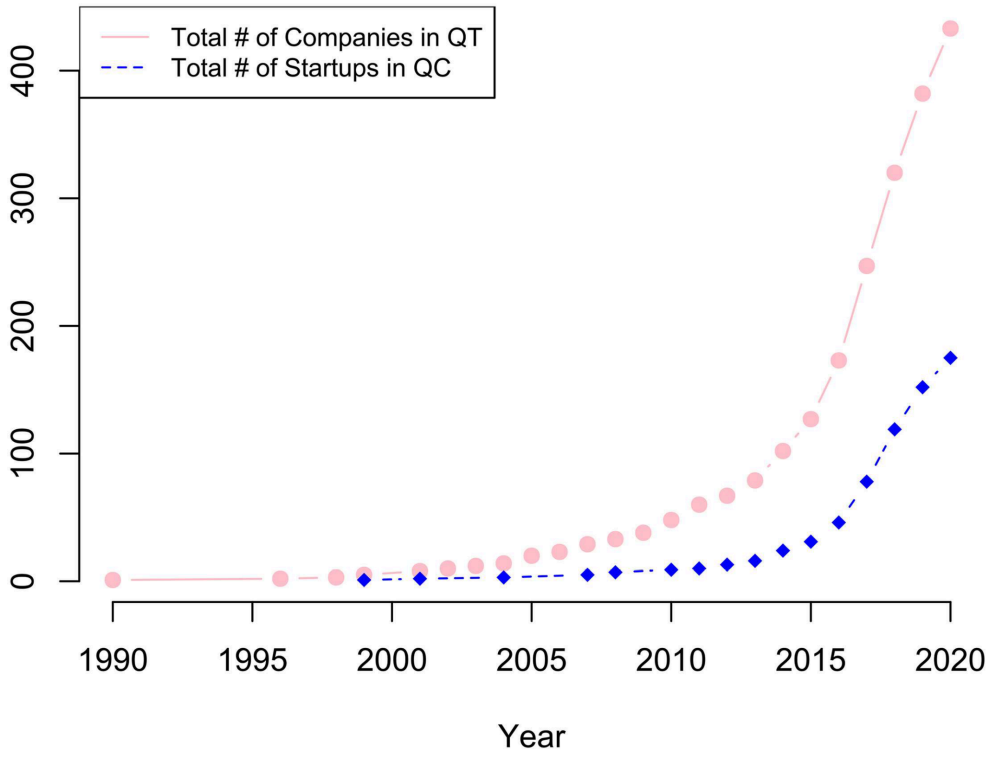


Figure 7.7. Total number of companies operating in quantum technologies and startups in quantum computing in years.

This inflection point has not gone unnoticed in the ethical, legal, and social aspects field as well, and one of the first special issues on QT titled The Societal Impact of the Emerging Quantum Technologies was published in the journal Ethics and Information Technology[88]. Topics such as

[88] ISSN 1388-1957 (print) 1572-8439 (web).

access to QT [91], the impact of QC on the future of scientific computing [92], responsible research and innovation in QT [93], and the potential impact of quantum computers on society [94] were discussed in the special issue. Since 2017, there has been growing interest in the societal impact of QT (and QC in particular). As of 2021, many researchers and commercial actors in the field have been calling the community to action regarding quantum ethics, which is a clear indication that there is a strong belief in the community that this technology will play a huge role in our future and should be developed ethically to avoid any undesired consequences while taking this quantum leap.

7.2.2.5 What is the next turning point in the development of quantum computing?

It is hard to predict technology. We can assume that everything works and imagine best-case scenarios. We can assume that nothing works and imagine a sort of quantum winter. In reality, it is likely the case that the changes ahead are impossible to envision today.

QC violates no known laws of physics. It, therefore, is thought of as perhaps the world's most challenging engineering problem. So when will we engineer such devices? Currently, we have seen progress so dramatic that it would be impossible for those working in the field to have imagined even five years ago. Perhaps this means that the state of QC even five years from today is difficult to predict. We still believe that five years from now, quantum computers will be in the early stages of development and still lack error correction and other essential features to realize all their potential.

Having said that, we do think that a quantum future is inevitable. This is the natural progression of technology. This is probably the ultimate limit of computers, perhaps until we can harness new powers in the cosmos. Humankind's trajectory is set on a quantum course. Companies such as Google, IBM, and the like are in this for research and long-term prospects.

When will we see another inflection point? It's hard to tell. The saying goes that knowledge begets knowledge, so development always seems to go increasingly fast. But the next jump might have to wait until practical problems of commercial value are sufficiently solved. This should take place perhaps around 2050. We do imagine that by then, this technology will already have changed the world in ways we cannot predict now.

Article 1.4: Building a quantum-ready ecosystem[89]

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Abstract
The emergence of quantum technologies has led to groundbreaking advancements in computing, sensing, secure communications, and simulation of advanced materials with practical applications in every industry sector. The rapid advancement of the quantum technologies ecosystem has made it imperative to assess the maturity of these technologies and their imminent acceleration towards commercial viability. The current status of quantum technologies is presented and the need for a quantum-ready ecosystem is emphasised. Standard Quantum Technology Readiness Levels (QTRLs) are formulated and innovative models and tools are defined to evaluate the readiness of specific quantum technology. In addition to QTRLs, Quantum Commercial Readiness Levels (QCRLs) is introduced to provide a robust framework for evaluating the commercial viability and market readiness of quantum technologies. Furthermore, relevant indicators concerning key stakeholders, including government, industry, and academia are discussed and ethics and protocols implications are described, to deepen the understanding of the readiness for quantum technology and to support the development of a robust and effective quantum ecosystem.

Keywords: quantum communication, quantum computing, quantum computing techniques, quantum cryptography, quantum information

1. Introduction

Quantum physics undoubtedly is one of the most successful scientific theories ever established in terms of the accuracy of its predictions. A global effort to use quantum phenomena,such as entanglement, superposition, and coherence to create radically new technologies has resulted in the verge of the second quantum revolution. We can already see quantum technology-based products prevailing in the market and an increasing number of companies [1], organisations, governments [2], and individuals making an effort to build a global quantum ecosystem. The prevalent question now is how to use quantum technology and not when quantum technology makes its appearance. Organisations have often used the term ‘quantum-ready’ to assess their current situation with regard to their ability to integrate quantum technology into their existing framework. But the applicability of the term has a wide range of implications in different case scenarios. Therefore, it is crucial to understand and define the term quantum-ready [3]. In this

[89] https://ietresearch.onlinelibrary.wiley.com/doi/full/10.1049/qtc2.12072

paper, we explore and provide a systematic understanding of quantum readiness, how to evaluate it, and how entities, organisations, or individuals can become quantum ready.

To begin, we define what quantum technology is as a category of new technology in Section 2. After classifying emerging technologies, we delve into the term quantum readiness and the need to address it in Section 3. Then, we establish the importance of being quantum-ready by applying the term to various innovation models in Section 4. This helps us in providing tools to understand quantum readiness and identify various indicators to take into consideration while evaluating quantum readiness. Finally, in Section 5 we explore the relevance and meaning of being quantum-ready for the key stakeholders in the ecosystem.

2. Classifying Emerging Technologies

To define quantum readiness, it is essential to understand the nature of quantum technologies. This can help to estimate the potential impact and implications of these technologies, as well as identify areas where further research and development are needed.

Quantum technologies find themselves classified as emerging technologies due to their current status of technological maturity and the nascent status of their practical applications. While their underlying principles, founded in quantum mechanics, have been established for over a century, the journey of translating these principles into practical, scalable, and reliable technologies is still in its early stages. Quantum computing, for example, is a field where significant research is ongoing to overcome key challenges, such as achieving fault tolerance [4], error correction [5], and scalability [6]. Quantum communication and quantum sensing, while more advanced than quantum computing, still need to clear hurdles related to miniaturisation [7, 8], reliability, and integration into existing infrastructures. Moreover, the commercial viability of quantum technologies is yet to be fully realised. While there is clear potential and growing interest from industry, widespread, large-scale commercial applications of these technologies are still on the horizon. One way to classify emerging technologies is based on their level of maturity [9, 10]. Firstly, early emerging technologies are technologies that are still in the early stages of development and may not yet have a clear application or commercial potential. Secondly, emerging-growth technologies have moved beyond the early stages of development and have begun to show commercial potential. These may still be facing significant technical or regulatory challenges. Finally, growth technologies are the ones that have achieved significant commercial success and are likely to have a significant impact on their respective industries.

Another way to classify emerging technologies would be based on their potential impact. Disruptive technologies are technologies that have the potential to fundamentally change the way an industry operates. They can create new markets or disrupt existing ones. When the term disruption is used, it generally indicates that an entirely novel method of operation has a substantial impact on how markets and industries currently perform [11]. Technology that supports the development of new goods, services, or business models without necessarily disrupting existing ones is known as enabling technology. Sustaining technologies improve the performance of existing products or services but do not create new markets or disrupt existing

ones. Another taxonomy of innovations was proposed by Freeman that groups them according to increasing importance [12]. This typology offers a conceptual framework for comprehending the contribution of quantum technology to a technological revolution. The typology consists of four types of innovations: incremental, radical, new technological systems, and technological revolutions. Smaller updates or changes made to the existing technology are referred to as incremental innovations. They may enhance the efficiency or quality of a product or service but do not fundamentally change its nature. Radical innovations involve important discoveries or developments that alter how a technology functions or is used. They frequently destroy established markets while offering new possibilities for expansion. The creation of completely new technological frameworks that integrate numerous related technologies or processes is called new technology systems. These systems frequently result in the development of brand-new industries or the evolution of already-existing ones. Fundamental core discoveries resulting in the formation of a cluster of new technologies that may revolutionise a wide range of sectors constitute the techno- logical revolutions. They are characterised by far-reaching and transformative impacts on various aspects of human life.

Disruptive technologies, as coined by Clayton Christensen [13], represent a transformative shift, a change in paradigms that disturb the status quo of existing markets or societal operations [14]. This characteristic makes quantum technologies, with their potential to redefine numerous fields, a clear candidate for disruptive technologies [15]. To comprehensively explore the potential of quantum technologies as disruptors, we can dissect them into three primary facets, each with historical parallels that underline their disruptive nature. Firstly, we turn our attention to quantum computing. This cutting edge computing paradigm, supported by quantum mechanics, bears a resemblance to the disruption caused by the invention of digital computers. The latter reshaped industries with an unprecedented surge in data processing speed and efficiency. Quantum computers, similarly, are poised to shatter current computational limits by accomplishing tasks at an exponential pace compared to their classical counterparts. The computational complexities within the scope of quantum computing, such as cryptographic problems, optimising logistical operations, and discovering new pharmaceutical compounds, to highlight a few, remain infeasible for traditional computing due to the exorbitant time frames demanded for computation. Perhaps most disruptive is the impact on data security where in comparison to classical computers, quantum computers are capable of deciphering encryption codes in a fraction of the time. Our second focal point is quantum communication technology, most notably Quantum Key Distribution (QKD). Poised to offer communication channels impervious to breaches, quantum communication has the potential to drastically transform the cybersecurity landscape. A close historical analogue is the proliferation of the internet, an innovation that fundamentally altered our modes of communication and information exchange. Finally, quantum sensing technologies, whose promise of ultraprecise measurements forecasts disruption across a multitude of sectors. GPS systems, medical technology, geological exploration, and more could see sweeping changes spurred by the sensitivity of quantum sensors. This potential disruption finds a historical echo in the introduction of radar technology, which indelibly imprinted its influence on navigation, meteorology, and warfare. The common thread across these potential disruptions is the departure from classical mechanics to quantum mechanics. This represents a paradigm shift as profound as the shift from mechanical to digital

systems in the 20th century, which was a transition that disrupted and reshaped our civilisation. While the field of quantum technologies as a whole is classified as an emerging technology, certain subfields are progressing at a faster pace, nudging them into the realm of emerging-growth technologies. These sectors have advanced from the initial stages of research and development to demonstrate tangible commercial potential putting them in the emerging-growth technologies category (Figure 1). By transcending the limits of classical technologies and enabling new capabilities in computing, communication, sensing, and materials, quantum technologies have the potential to transform various aspects of human life and reshape the global economy making it a technological revolution [16]. To fully comprehend the potential effect of these technologies and how to prepare for the future, governments and industry leaders must categorise new innovations in the frame- work of quantum technologies. Policymakers and business leaders can hasten the development of quantum technologies and make sure they are well positioned to benefit from this revolutionary technology by anticipating potential disruptions, identifying areas for research and development, identifying potential applications, and informing the government on policy decisions.

3. Addressing Quantum Readiness

Although quantum technology is still in its infancy or emerging stages, it is developing quickly. Rapid advancements in quantum technology can expand the global economy by billions of dollars [17]. Hence, it is vital to be prepared and adapt to it. In addition to its fast-paced growth, the technology is inherently different from current technologies and will be massively disruptive for most sectors. This technology will likely have a disruptive innovation effect on operations, services, and products, giving companies that exploit it early a significant competitive advantage. In areas where quantum technologies are anticipated to have a big influence [18], nations that invest in and embrace quantum technology first will have a competitive edge. Governments that are not quantum-ready run the danger of falling behind in these sectors and may find it difficult to compete with those who have made quantum technology investments [19]. Quantum technologies have the potential to make sophisticated computing, secure communication, and encryption possible [20]. Non quantum-ready entities and organisations may be more susceptible to cyberattacks and other security threats [21, 22]. Quantum computers can defeat current encryption schemes, leaving sensitive data open to theft or abuse. The protection of national interests and citizens will be improved in nations that are quantum-ready. Research advancements in areas such as materials science, drug development [23], and artificial intelligence [24] will be made possible by quantum technologies. Researchers must hasten the progress of science and produce important new discoveries by focusing on quantum readiness. Quantum computing can be used to model intricate chemical processes, speeding up the development of novel medicines and materials [25], and has the potential to transform banking by enabling financial institutions to carry out hitherto impractical sophisticated computations and risk analysis [26]. Global problems including climate change, energy efficiency, and sustainable agriculture might be solved by quantum technologies [27]. Countries can support sustainable development and the welfare of their citizens by adopting quantum technologies that address these issues [28]. Quantum computers can potentially be utilised to

optimise energy distribution and cut down on waste, while quantum sensors could be used to monitor environmental conditions and increase crop yields [29].

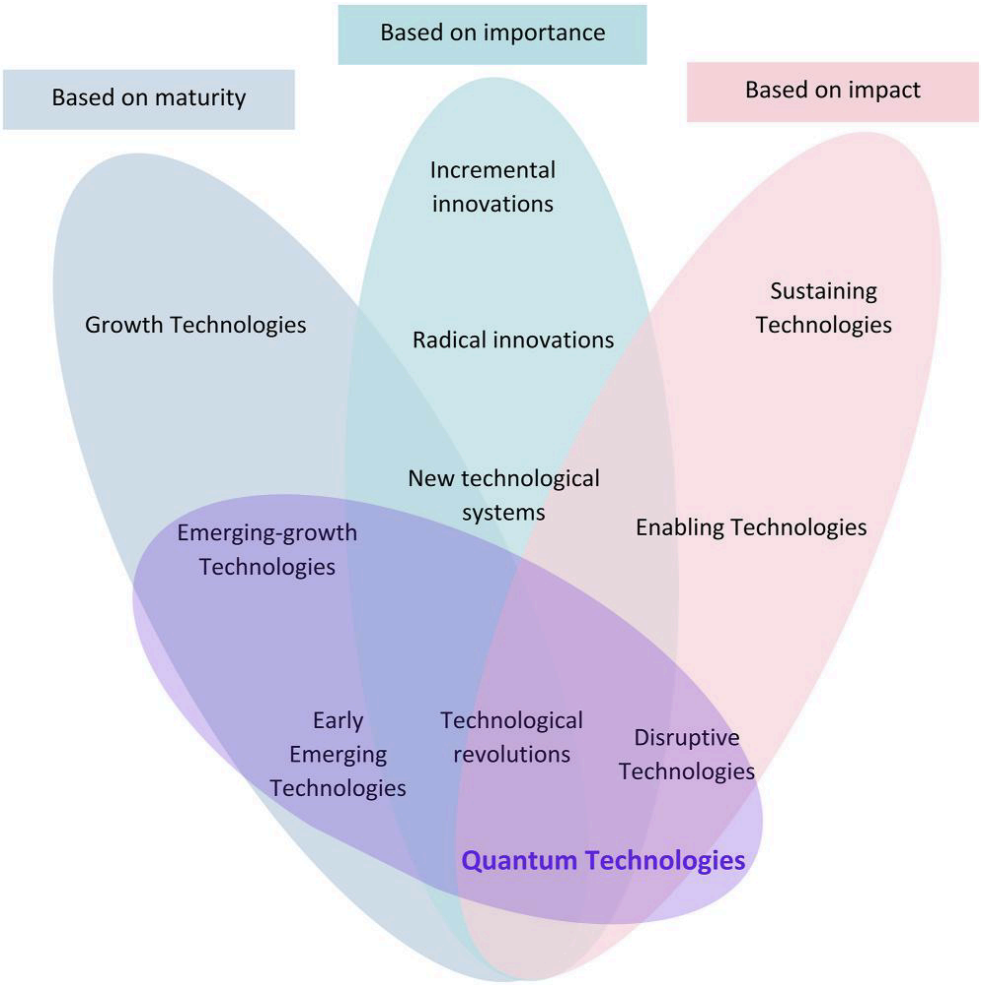


FIGURE 1 Classification of emerging technologies and status of quantum technologies.

In the near future, quantum readiness will play a key role in deciding if a business/organisation thrives or recedes. For example, Quantum Key Distribution (QKD), has the potential to revolutionise the field of cryptography. QKD allows for the secure exchange of encryption keys by exploiting the principles of quantum mechanics. Quantum computers may make current encryption techniques like RSA obsolete since they may be able to decrypt data significantly faster than traditional computers. The cybersecurity landscape will drastically change as a result of this disruption [30], necessitating the creation and deployment of new cryptographic algorithms that are resistant to quantum computing. In comparison to classical computing, quantum computing can more effectively optimise complex financial models, portfolio management, and risk assessment [31]. As a result, financial institutions may optimise investment strategies, more precisely assess risks, and more successfully identify fraud, which could potentially have a significant impact on the financial sector.

Since quantum technology can render previous technical knowledge outdated and maintain technological, industrial, economic, and social transformation, it shares many traits with General-Purpose Technologies (GPTs). Changes in techno economic paradigms brought about by GPTs impact all sectors of the economy and continue the long term process of economic progress in human civilisation. Furthermore, to support an entire and a functional quantum ecosystem built on solid physical infrastructures, highly skilled human resources, and suitable technological systems, the evolution of this technology requires time, research and development investments, carefully chosen research policies, and key strategic decisions of governments and industry. Therefore, quantum readiness comes in with a first-mover advantage and the power to shape the direction of the technology. For instance, organisations in the pharmaceutical and materials sectors that use quantum computing to identify new drugs or design new materials might accelerate research and development efforts. These businesses can obtain a first-mover advantage by discovering potential drug candidates or novel materials more rapidly and accurately than rivals, that use classical computing approaches, enabling them to sell new products quickly and possibly secure patents earlier allowing them to thrive [32].

For organisations to be competitive, safe, and economically prosperous in the future, addressing quantum readiness is essential. Countries can capitalise on this game-changing technology and promote science and sustainable development by investing in quantum technologies and building a strong quantum ecosystem. Although there are many obstacles to creating and using quantum technology, the advantages are too enormous to ignore. Organisations can make sure they are ready to profit from this innovative new technology by collaborating to address the issue of quantum readiness.

4. Diffusion of Emerging Technology

Building on our understanding of quantum technologies' potential impact, it becomes imperative to delve into the concept of quantum readiness as discussed in the previous sections. But as we navigate this pioneering landscape, the importance of having tools to gauge the progress of quantum technologies cannot be overstated. Such instruments would allow us to systematically assess the evolution of these technologies, drawing from various conceptual models and metrics. They can serve as compasses for interested entities, whether they are research organisations, industry stakeholders, or policymakers. With a tangible sense of where we stand on the quantum technology trajectory, we can better identify the risks involved, thus enabling more strategic planning. The subsequent examination of quantum readiness is therefore not only a scholarly exercise but a crucial step in mobilising the global quantum ecosystem.

Radical innovation models refer to frameworks used to explain how new and emerging, transformative technologies or business models emerge and disrupt existing industries or markets. It is still early to see the full impact of quantum technologies, but many (including the authors) expect them to be a highly transformative and disruptive set of technologies.

Therefore, we argue that investigating and thinking about quantum technologies via radical innovation models is a suitable theoretical framework. One such model is the Disruptive

Innovation Model developed by Clayton Christensen, which explains how new technologies or business models can initially serve niche markets before eventually disrupting and overtaking established ones [33].

Another potentially relevant concept is pervasive innovation, which refers to the idea that innovation can occur across all aspects of society and in all sectors of the economy, leading to profound changes in how people live, work, and interact with one another [34]. This can be thought of in relation to the idea of the techno-economic revolution, a concept which refers to the profound economic and societal changes that can result from the emergence of new technologies or industries [35]. These revolutions often involve the displacement of existing industries, the creation of new ones, and shifts in the distribution of wealth and power. Examples of techno-economic revolutions include the industrial revolution, the information revolution, and the ongoing transition to a digital economy.

Techno-economic paradigms should also be mentioned here in its relation to techno-economic revolutions. These are overarching frameworks that guide technological innovation and economic growth in a particular period. They represent the dominant technological and economic structures, processes, and institutions that shape innovation and growth in a given era [36]. Techno-economic paradigms are characterised by a set of shared beliefs, values, and practices that define the boundaries of what is considered technically feasible and economically viable. It is debatable whether quantum technologies should be viewed as a potential new techno-economic paradigm or as a subset of digital transformation. However, the analysis and recommendations developed in this paper are irrespective of either case. Quantum technologies, either by themselves or as a part of the constellation of the technologies enabling the transition to the next techno-economic paradigm, will play an important role in the following decade.

Both radical or pervasive innovation, techno-economic revolutions and paradigms are important concepts to consider in the context of the period we are experiencing in relation to the second quantum revolution and associated quantum technologies. By acknowledging the potential for innovation to arise from unexpected sources and recognising the profound economic and societal changes that can result from new technologies, organisations can better prepare for and navigate the challenges and opportunities of the innovation process. In this regard, one can turn to transitional studies, which focus on how organisations or industries can manage and navigate transitions to new technologies or business models. These studies examine the challenges, opportunities, and strategies involved in moving from current practices to new ones [37].

Quantum readiness, in this context, refers to the ability of organisations to adopt and leverage quantum technologies for competitive advantage, especially during the transitional period where profound economic and societal changes may occur due to the radical and pervasive nature of quantum technologies. This set of technologies, including quantum computing and quantum cryptography, has the potential to revolutionise many vertical industries such as finance, healthcare, and logistics, but it also requires significant investments in infrastructure, expertise,

and cultural change. Therefore, this process of getting ready for and enabling the second quantum revolution can be thought of as a highly entangled process.

The application of radical innovation models and transitional studies can help organisations prepare for and navigate the transition to quantum readiness. For example, the Disruptive Innovation Model can provide insights into potential market disruptions and the emergence of new business models in the quantum space, while transitional studies can help organisations identify and manage the barriers and the enablers of quantum adoption, such as funding, talent, and regulatory frameworks.

In summary, radical innovation models and transitional studies are valuable tools for organisations seeking to become quantum-ready. By understanding the dynamics of radical innovation and managing the transition to new technologies, organisations can position themselves for success in the emerging quantum landscape. Three common tools that are widely used in this literature are the well-known S-curve [38], the Technology Readiness Levels (TRLs) framework [39, 40] and Technology Commercial Readiness Levels (TCRLs) framework [41].

4.1 S-curve analysis

The S-curve [42] diffusion model is a useful tool for predicting and understanding the adoption and diffusion of new technologies, including quantum technology. It can be used to predict the rate of adoption of quantum technology and identify potential opportunities and challenges. For example, companies can use the S-curve model to identify when quantum technology is likely to reach the growth phase and plan accordingly [43, 44]. This can include investing in research and development, building partnerships, and developing new products and services.

As the growth of many innovations follows the fundamental pattern, the uptake of innovation is frequently represented in these terms in diffusion analysis [45]. Slow adoption is followed by a period of high growth, which is then followed by slower growth as the majority of potential adopters have already adopted the new product (Figure 2) [46]. S-curve diffusion assessments frequently highlight the differences between early and late users. Early adopters tend to be wealthier, more educated, connected to mass media etc. on an individual level. We may also assume that there is a pattern of diffusion across business sectors, with some being early adopters and some being followers. This is true if we look at the dissemination of significant new technologies that can be used for a variety of purposes. Early adopters, for instance, frequently work in high-tech industries and are presumably more closely connected to the fields where the technology was initially produced and/or used. The analysis can be approached through the lens of the industry life cycle and product life cycle [47]. The basic idea behind the industry life cycle approach is that sectors are likely to mature over time. Their operations become conventional, their goods become more standardised, and the production tools they need to use become more affordable or easier to use. They rely less on highly skilled labour.

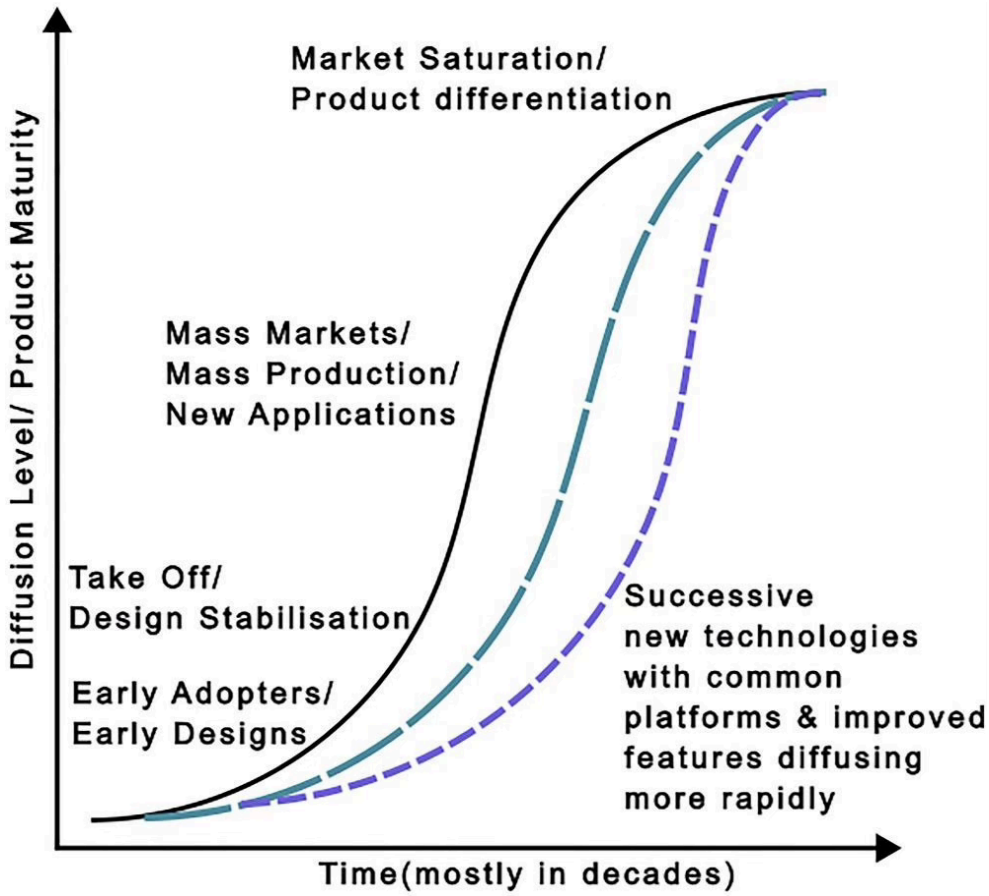


FIGURE 2 The S-curve analysis of emerging technologies.

The product life cycle approach makes additional comments that are especially relevant when taking the dynamics of new technologies into account. This strategy incorporates the findings of several innovation studies as well as the concepts of diffusion and industry cycles. Here, the essence of the technology itself is more important than how the market or industry develops. According to the product life cycle concept, early versions of inventions are frequent, even when technologically advanced, relatively simple and primitive in comparison to their later versions. Not merely because the marketplaces are still in their infancy, but because the early generations of innovations appeal to very few customers. There is a lack of understanding, on the user side of their existing and future capabilities, and on the supplier side, of precisely what skills will be valued and how they may be employed. It also prompts the idea that there could be weak connections between inventors and numerous prospective consumers and use cases of the technology in the early stages of product creation and distribution. Complementary goods and services are either unavailable or not generally accessible in the early stages of development. Comparing the essential components to subsequent versions of comparable products, the key products are likely to be more expensive and less reliable. Early versions of goods are likely to need significant technical expertise for their manufacturing and usage, but later versions may make use of these abilities as a common practice. If the products succeed, people will become more aware of them, invest more in them, and acquire more skills using them and their markets will grow. The technology itself will evolve, which is essential. The product has undergone

redesigning to make it more durable, user-friendly, and capable of more effective manufacturing. New entrants, who could bring fresh concepts for innovation, join the early suppliers, who have shown the potential for a sizeable new market. Several innovation approaches frequently compete with one another, with the winner establishing the design paradigm to which all others should adhere. If the first providers are small firms, big businesses are liable to substantially change the nature of the competition in the market possibly by acquiring the smaller firms. Large enterprises with greater marketing capabilities have the capability to boost the diffusion process and the creation of a dominant design. Later, as the market expands, the emphasis on innovation often shifts away from fundamental product/technology innovation and towards providing enhanced quality before shifting to process innovation that is scalable and economical. With supplementary goods and services, enabling technologies, increased functionality, and greater adaptability, the product becomes more user-friendly and requires fewer high-level skills to utilise. There can be a shift from technology-push to demand-pull. Successful inventions have an extended development phase once they are introduced to the market, not just while they are precommercial prototypes in research and development institutions, but as providers discover what consumers want. Users, on the other hand, acquire knowledge about the product and successful usage techniques.

When it comes to quantum technology it gets tricky, as it itself branches into several technologies, including quantum computation, sensing, communication, cryptography, and more. Each of these individual technologies stands at different stages. Furthermore, some of the technologies involve similar architectures and platforms, although currently there is no clear winner for which platform will be adopted in general or within its branches. Therefore, it is worthwhile to look at quantum technology in general to assess the current scenario. The adoption rate of quantum technology is examined over time, and it is compared to the adoption rates of other technologies, in the S-curve analysis. Quantum technology adoption also entails evaluating the elements influencing or impeding its uptake as well as projecting its possible future uptake which we call indicators. By considering indicators such as research publications and patents, investment, commercial products and services, talent pool, technical advancements, industry partnerships, and government policies, we can evaluate the current status and potential future of quantum technology [48]. This understanding is essential for determining the quantum readiness level, which is critical for realising the full potential of quantum technology.

When we say adoption of a technology, we refer to the extent to which the technology is being used or integrated within a sector or an ecosystem reflecting acceptance of the technology by consumers, industries, or society as a whole. Determining and choosing the Key Performance Indicators (KPIs) can help us infer the level of adoption by showing where the technology is in its life cycle. For example, an increase in research publications over time suggests that the technology is gaining interest in the academic community. An increase in investment in a particular technology indicates growing confidence in its commercial potential. Start-ups represent the presence of commercial products and services which is a clear sign that a technology is being adopted. It is essential to recognise that these indicators do not occur in isolation, but rather interact and influence each other. For example, an increase in research

publications can lead to more patents, which can then attract more investment. This cascading effect can accelerate the technology's movement along the S-curve, hastening its adoption. Plotting these indicators over time can give us a visual representation of the technology's progression along the S-curve of adoption. It provides a multi-dimensional perspective of the technology's adoption status, with each indicator representing a different aspect of the technology's life cycle.

To see a general trend of the growth and diffusion of quantum technologies in general, we collected data for various indicators over time and plotted it on the same time scale with the total number of each indicator normalised to one (our code reads in data from four CSV files containing the number of startups, patents, publications, and private investments for each year. It then normalises the data so that the maximum value for each category is equal to 1 for a better visualisation to compare these trends) in Figure 3. For the collection of data on publications, we used bibliometric tools such as the *Web of Science* (WoS) database and search query as done in ref. [49]. For patents, we used the data recently published in the paper [50]. For start-ups data, we used the numbers from ref. [1] and the database maintained and updated by QURECA. For private investments, we used the data from the Quantum Technology Investment Update 2022 report published by The Quantum Insider [51]. When we plotted all these data against years, we see a general trend of take-off of quantum technologies, indicating that now is the perfect time to become early adopters peak simultaneously, it signifies a strong momentum behind the technology. This synchronisation is often seen when the technology is transitioning from the innovation stage to the early adoption stage in the technology adoption lifecycle.

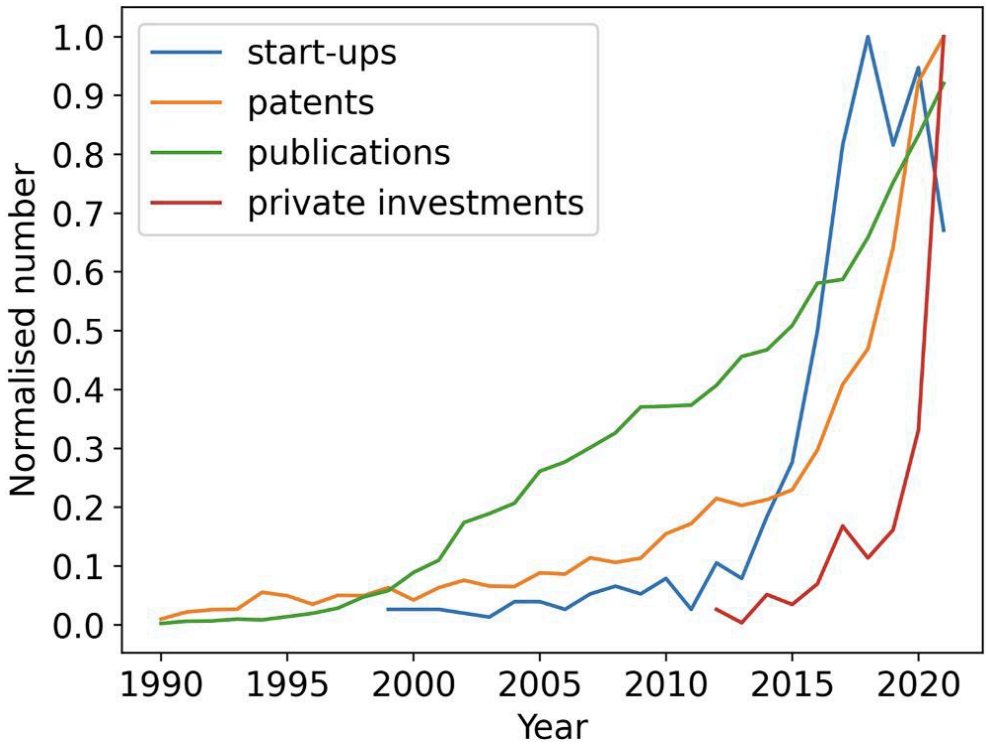


FIGURE 3 Various quantum readiness indicators over time for quantum technologies.

These factors suggest a good time for early adoption, they do not eliminate the inherent risks associated with emerging technologies. However, emerging technologies are inherently risky and can fail for a variety of reasons, including technical challenges, market acceptance issues, regulatory problems, and many others. An alignment of these indicators does suggest that the technology is maturing and moving towards broader market adoption. This can be an ideal time for organisations that are comfortable with a certain level of risk to become early adopters. By doing so, organisations may benefit from leveraging the technology before it becomes widespread, while also having a chance to shape the technology's development and application in their industry. Being an early adopter of quantum technologies can provide organisations with a range of benefits. It can help them to stay ahead of the curve giving them a competitive advantage, improving productivity, innovating new products and services, and shaping the direction of the technology. Although we could see some dips in 2023, it could be an implication of various factors away from normal conditions such as the COVID-19 pandemic and more.

Forecasters must be aware that there are sometimes variations in the norm. Even though S-curves typically offer quite good fits to empirical data, in reality, they are frequently disrupted by other factors such as wars and economic downturns. Innovations can also replace one another before a certain innovation is adopted by all its prospective users, and a rival technology may supplant it.

4.2 Technology readiness levels for quantum technologies

Technology Readiness Levels (TRLs) are a method of measuring the maturity of a technology by determining its level of development, testing and integration [52]. The TRLs provide a common framework for evaluating and communicating the maturity of a technology and can be used to identify areas where further research and development are needed. For quantum technologies, it makes more sense to use TRLs to assess the readiness of individual branches or at an individual product level. It is crucial to identify the quantum technology to be assessed and its intended application(s). This will help in identifying the specific requirements for the technology and the performance metrics needed to assess its TRL. Then one must determine the TRL criteria for the quantum technology under assessment. This can include factors such as the level of technical feasibility, the maturity of the design, the level of testing and validation, and the readiness for deployment. Evaluating the technology against the TRL criteria by analysing the performance data from experimental studies, simulations, and tests, and comparing the results helps assign a TRL value. This should reflect the technology's current stage of development and the level of maturity it has achieved. It also reflects the level of confidence with which the technology is ready for deployment in the market. Based on this TRL, one can then develop a roadmap for the technology. This involves identifying the key development milestones needed to reach the next TRL and the associated resources and investments required.

TRLs are typically defined on a scale of 1–9 [53, 54]. The same can be adopted for quantum technologies with the addition of ethics protocols for the branch of quantum technology in consideration. The first four levels usually address the most fundamental technical research involving, mostly, laboratory results given the sort of research, technological advancement, and

innovation being addressed. From levels TRL 5 through TRL 6, technological development would then proceed until the first prototype or demonstrator is obtained. Projects involving technological innovation would fall between TRL 7 and TRL 9, as this type of innovation necessitates the launch of a new product or service onto the market, which involves passing the necessary tests, certifications, ethics, and approvals. These stages entail deployment or extensive implementation. Assessing the readiness of new technology products is important for understanding their maturity and potential for commercialisation.

We have formulated standard Quantum Technology Readiness Levels (QTRLs) taking inspiration from the ones set for general TRLs and TRLs for artificial intelligence technology to help assess a quantum technology in more accurately as shown in Figure 4. The description and expected outcomes from each of these levels are described below:

1. QTRL 1 (Basic principles observed): Research into the basic principles of quantum phenomena is at present being conducted. This might involve researching various phenomena such as quantum superposition, entanglement, and coherence as well as creating theoretical equations and models to explain these concepts.

2. QTRL 2 (Technology concept/application formulated): Based on the concepts observed in QTRL 1, researchers develop a particular quantum technology concept or application at this phase. This entails the formation of a distinct technical vision and goals and may include concepts for quantum computing, communication, or sensing applications.

3. QTRL 3 (Analytical and experimental proof of concept): Researchers working at this level offer analytical and experimental evidence that the technological concept or application is feasible. This typically involves laboratory experiments and simulations to validate the technology's functionality, performance, and potential advantages over classical technologies.

4. QTRL 4 (Quantum technology validated in lab): Quantum technology systems or components are developed and assessed at QTRL 4 in a controlled lab setting. This stage focuses on the integration of individual quantum components into a larger system and the testing of their performance, reliability, and scalability.

5. QTRL 5 (Quantum technology validated in relevant envi- ronment): In this phase, researchers validate the system's performance in environments that closely resemble real- world applications. This might involve testing quantum communication systems over long distances, assessing the performance of quantum sensors in realistic settings, or benchmarking quantum algorithms on prototype quantum processors.

6. QTRL 6 (Quantum technology demonstrated in relevant environment): QTRL 6 requires a demonstration of a fully functional system or subsystem within a relevant environment. This could include a quantum communication network connecting multiple users, a quantum sensor deployed in the field, or a quantum processor executing a specific algorithm to solve a real-world problem.

Environment	Goal	Product / Evaluation	Outputs	QTRL	Description
Laboratory	Research	Proof of concept	Research articles published on the fundamental principles of the quantum technology	QTRL 1	Basic principles observed
			Development of specific quantum technology or application based on fundamental principles	QTRL 2	Technology concept/application formulated
			Laboratory experiments and simulations to provide experimental evidence and potential advantages over classical counterpart.	QTRL 3	Analytical and Experimental proof of concept
		Prototype	Laboratory testing and integration of quantum components into larger system	QTRL 4	Quantum Technology validated in lab
Simulation	Development		Quantum technology's performance in environments that closely resemble real-world applications	QTRL 5	Quantum Technology validated in a relevant environment
			Demonstration of a functional prototype in a relevant environment	QTRL 6	Quantum Technology demonstrated in relevant environment
Operational	Implementation		Fully integrated, functional prototype level tests carried out in the operating environment	QTRL 7	Prototype demonstration in operational environment
		Commercial product/service (certified)	Rigorous testings in final configuration. Ethics and protocols taken into consideration	QTRL 8	System complete and qualified
		Deployment	Successfully deployed and used in real-world applications	QTRL 9	Successful project operations

FIGURE 4 Quantum Technology Readiness Levels (QTRLs) description, representation, and expected outcomes.

7. QTRL 7 (Prototype demonstration in operational environment): At this level, a fully integrated system prototype is demonstrated in an operational real-world environment. This may involve field testing of a quantum communication system for secure data transmission, deploying a quantum sensor for environmental monitoring, or running a quantum computer to solve complex optimisation problems.

8. QTRL 8 (System complete and qualified): QTRL 8 is achieved when the system has been completed and qualified through rigorous testing and demonstration. This includes achieving all performance requirements, addressing any identified issues or limitations, and demonstrating a high level of reliability and robustness. Ethics and other protocols are also taken into consideration and checked.

9. QTRL 9 (Successful project operations): When the quan- tum technology has been successfully deployed and used in practical real-world applications or missions, the final QTRL has been reached. This may entail the widespread use of quantum sensors in a variety of businesses, the commercial availability of quantum computing services, or the use of quantum communication technologies for secure data transmission.

One way to assess the readiness of a new technology product is to use a readiness-vs-generality chart [55]. The same can be used if one wants to evaluate the readiness of a specific quantum technology-based product and not a branch in general. One must identify the different layers of the capability of the product in relevant environments and then compare it against the TRL of each layer of capability. For instance, Forschungszentrum Jülich defined a set of TRLs for quantum computing [56]. The theoretical foundation for quantum computing (annealing) is developed when quantum computing technology is at QTRL 1. Once the fundamental device principles have been investigated and applications or technologically pertinent algorithms have been developed, the technology reaches QTRL 2. The fundamental components of quantum computing systems, physical qubits that have been fabricated imperfectly, are at QTRL 3. Laboratory tests are then designed to verify the theoretical predictions of qubit characteristics and then proceed to the fabrication of multiple qubit systems with the classical control unit in QTRL 4 stage. Technology for QTRL 5 quantum computing consists of parts that are incorporated into a tiny quantum processor without error correction. At QTRL 6, there are components assembled into a miniature error-correcting quantum processor. They are rigorously tested with various quantum algorithms and benchmarked. In the QTRL 7 stage, the prototype is tested for solving small, but relevant use-case problems. Once the prototype is made scalable and qualifies for all necessary tests, it advances to QTRL 8 stage. Finally, when the prototype quantum computer exceeds the power of the classical com- puters in specific problems, it is labelled as QTRL 9. This acts as a critical tool for them to assess their current quantum readiness level and helps in strategising a roadmap for their prototype and planning future steps of action and set goals. Hence, it is of utmost importance that QTRL assessment is conducted by qualified experts with a deep understanding of the technology and its development. It is also important to set standardised QTRL levels in each branch of quantum technology so as to make meaningful comparisons with other competing organisations/platforms. One of the major highlights of Quantum.Tech, a conference held in 2022 in Boston, Massachusetts, USA was assessing the TRLs for various branches of quantum

technology. In comparison to quantum sensing and quantum computing, quantum communication, such as QKD, is viewed as the more developed domain (QTRL 7) for many future implementations while quantum computing was seen to be at QTRL 3 [57]. Another report in 2021 to assess quantum readiness for military applications provided a detailed report on various TRLs for different quantum technologies [58]. Taking data from all these reports and roadmaps, we provide an assessment of current TRLs for various quantum technologies and a time horizon indicating the expected time it would take to achieve a QTRL of 9 for these quantum technologies (Figure 5).

We can clearly see that quantum technologies are at different QTRLs. By considering diverse applications and deployment platforms, the QTRL variance and time horizon assumptions become much more complicated. Building on these reports provides a snapshot of trends and should reduce sampling bias. In conclusion, the QTRLs of different branches of quantum technologies vary widely, with quantum computing being in the earliest stages of development and quantum communication and cryptography being more mature. Significant progress has been made in recent years in all branches of quantum technologies, but challenges remain in scaling the technology to meet the requirements of practical applications. It is crucial to keep a track of the QTRL levels of these branches in order to stay ahead of the curve and be quantum-ready.

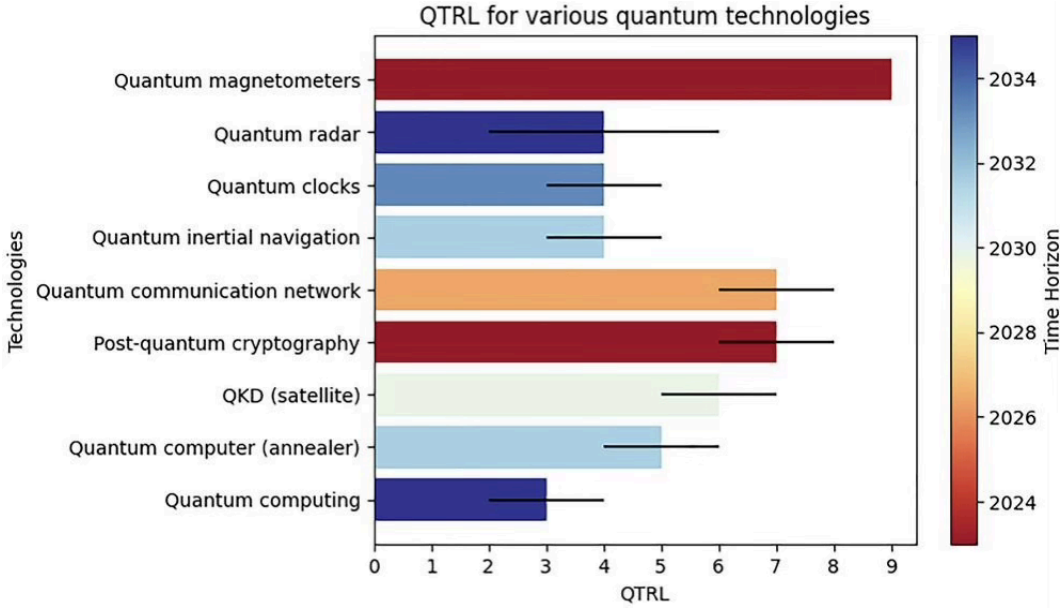


FIGURE 5 QTRLs and time horizon expectations (with error bars) for several quantum technologies.

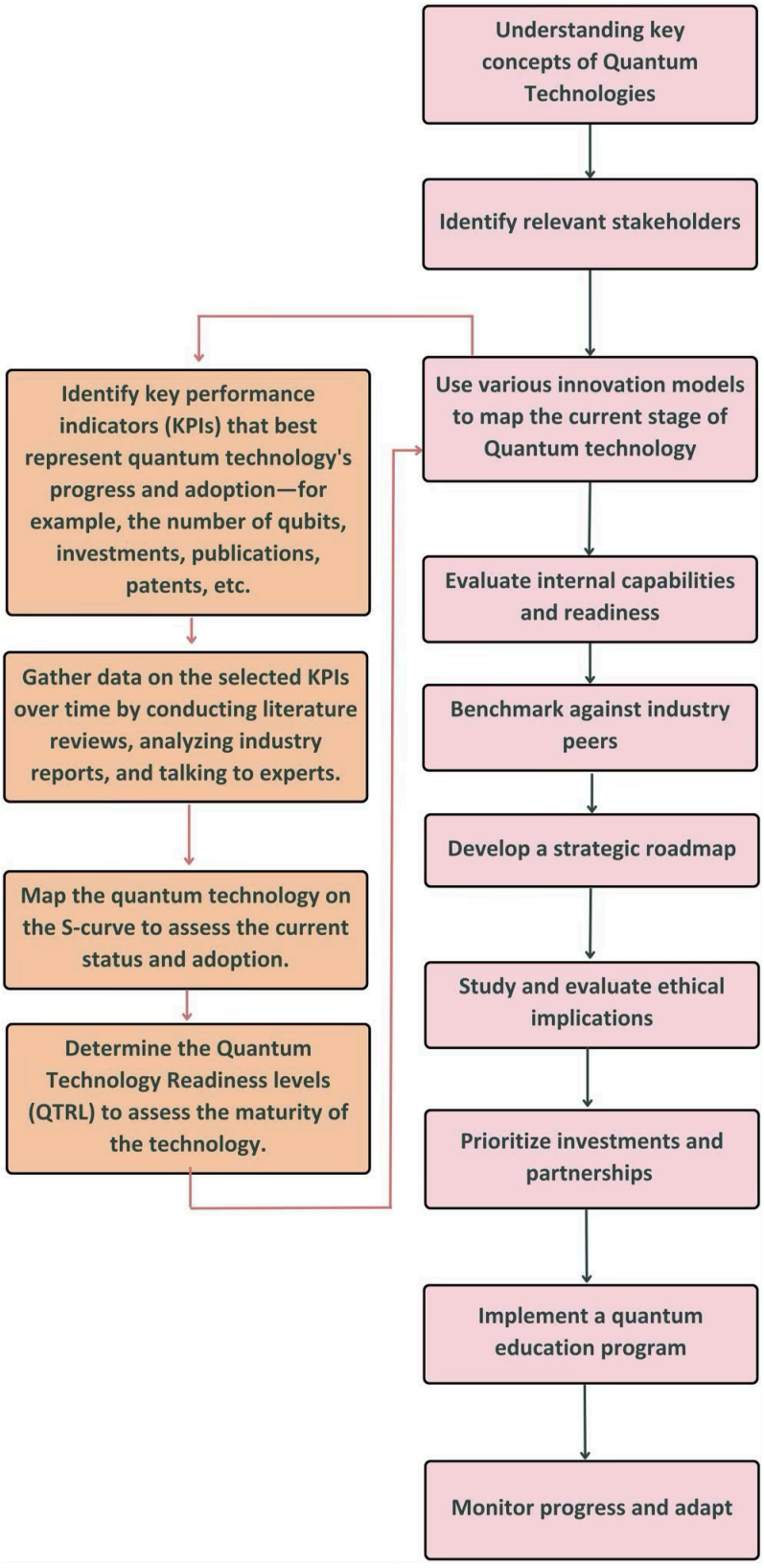


FIGURE 6 Flow chart describing the steps to follow to be quantum-ready.

With all these tools and information, we have devised a roadmap or a flowchart with detailed steps to assess quantum readiness (Figure 6). It will help businesses and organisations to assess their quantum readiness or to develop a strategy to be quantum-ready. It can be summarised as follows:

1. Understanding key concepts of Quantum Technologies: Gain a basic understanding of quantum physics principles, such as superposition, entanglement, qubits, and sensors.

2. Identify relevant stakeholders: Assemble a team of stake- holders from different departments such as research and development and executive leadership. This team will be responsible for driving the assessment process and implementing the findings.

3. Use various innovation models to map the current stage of quantum technology: Identify and gather data over time for various KPIs (Key Performance Indicators) and map them on the S-curve, evaluate TRL to assess maturity of quantum technology.

4. Evaluate internal capabilities and readiness: Evaluate your organisation's current capabilities and readiness to adopt quantum technology. Identify any gaps in knowledge, expertise, or resources that need to be addressed.

5. Benchmark against industry peers: Analyse your competitors and industry leaders to understand their quantum readiness and strategies. Identify best practices.

6. Develop a strategic roadmap: Create a strategic roadmap outlining your organisation's plan to adopt and implement quantum technology. This should include short-term and long-term objectives, as well as a timeline for implementation.

7. Study and evaluate ethical implications: Explore, assess, and adapt ethical and societal responsible use of quantum technology.

8. Prioritise investments and partnerships: Determine the resources required to achieve your quantum technology readiness goals, such as investments in hardware, software, and talent. Prioritise investments based on potential impact and return on investment. Identify potential partners, such as universities, research institutions, and technology providers, to collaborate on quantum technology initiatives.

9. Implement a quantum education programme: Develop and implement a comprehensive quantum education programme for your organisation. This may include training sessions, workshops, and seminars to ensure all relevant stakeholders are informed about the latest developments in quantum technology.

10. Monitor progress and adapt: Regularly review and update your quantum technology readiness assessment and strategy based on new developments in the field. Continuously evaluate your organisation's progress and adjust as necessary to stay on track with your quantum technology goals. Publish these assessment reports.

4.3 Commercial readiness of quantum technologies

While Technology Readiness Levels (TRLs) provide an assessment of a quantum technology's technical maturity, they do not account for its market readiness or commercial viability. Quantum Commercial Readiness Levels (QCRLs) offer a strategic framework for determining the market readiness of quantum technologies. They examine the commercial aspects of these technologies, focusing on their potential to generate revenue, their fit within the market, and their capacity to navigate the regulatory environment [41, 59]. We provide a framework to assess it as follows:

1. QCRL 1 (Problem-Solution Fit): At QCRL 1, the primary goal is to demonstrate that a quantum technology can offer a viable solution to an identified problem. It is an ideation phase, where researchers and developers are confirming that their quantum-based solution aligns with a particular need or problem in the market involving rigorous problem definition and in-depth market research crucial to that time. The identified problem may be broad, encompassing challenges in various sectors like cybersecurity, material sciences, logistics, or drug discovery, among others. It is essential to establish a preliminary hypothesis for how the technology can address these issues and identify potential customer segments who might benefit from the solution.

2. QCRL 2 (Market-Solution Fit): The focus now is on validating the proposed solution within the potential market. This involves in-depth market research to understand the needs and preferences of potential customers, evaluating the competitive landscape, and performing a preliminary assessment of the regulatory landscape. The aim is to finetune the solution to fit the market needs better and establish initial relationships with potential customers or partners. It is at this stage that a technology might pivot or refine its focus, based on market feedback and competition.

3. QCRL 3 (Minimal Viable Product [MVP] Development): Upon reaching QCRL 3, the technology has progressed to a point where a minimal viable product (MVP) can be

   developed. This MVP encapsulates the essential functionality that addresses the identified problem, serving as a tangible representation of the technology's potential in the real world. It is used to solicit feedback from early users, allowing for further refinement of the product based on actual user experience. This stage involves significant interaction with potential customers, taking in their feed-back, and adjusting the product's design and function accordingly.

4. QCRL 4 (Product-Market Fit): A full-fledged, commercially viable product has been developed now based on feedback from the MVP stage. This stage validates the product's market fit, demonstrating that there is a market demand for the product, and that the product satisfies that demand adequately by rigorous benchmarking. Business models are tested and revenue generation strategies are defined. Early sales to innovators or early adopters have been achieved, providing evidence of the product's market fit.

5. QCRL 5 (Scaling and Growth): In the final stage of commercial readiness, where the technology is ready for full commercialisation and scaling. The focus is on growing sales, expanding into new markets, and optimising the product based on customer feedback and market dynamics. The production and distribution processes have been solidified, the supply chain has been identified, there is a clear marketing strategy, and any pertinent regulatory hurdles have been navigated by this time.

Quantum technologies often require significant investment and time for development. By assessing the QCRLs, investors and developers can better understand the commercial risks associated with a particular technology and make informed decisions about resource allocation. It helps in identifying potential market barriers early, which can be addressed proactively, reducing the likelihood of costly failures down the line. Furthermore, the QCRLs facilitate regulatory planning, helping companies anticipate potential regulatory hurdles and strategise accordingly. Finally, by showcasing a technology's commercial readiness, QCRLs can instil confidence in potential customers, accelerating the adoption and acceptance of quantum technologies in the market. In essence, QCRLs provide a pragmatic framework that is essential for strategic decision making and for driving the successful diffusion of quantum technologies across various sectors.

Mapping QCRLs to QTRLs is an essential step in the journey of quantum technology development and commercialisation. This process brings a necessary cohesion between the technical progression and market readiness of a quantum technology, offering a comprehensive view of its trajectory from laboratory to market. The initial QTRLs (1–3), where technologies are in the research and development phase, correspond to QCRL 1, where the problem-solution fit is being explored. As the technology progresses to the prototype phase (QTRLs 4–5), it aligns with QCRL 2 and 3, where market validation and MVP development are occurring. At the demonstration stage of the QTRLs (6–7), technologies typically reach QCRL 4, where the product-market fit is established, and early sales are achieved. At the higher QTRLs (8–9), where the technology is ready for deployment or already in use, they align with QCRL 5, indicating that the technology is ready for full commercialisation and scaling. However, it is essential to understand that once a technology reaches QTRL 9, there can still be significant barriers to widespread adoption, including cost, regulatory hurdles, workforce training, and more. A common issue in technology development is the ‘valley of death’, a phase where a technology, despite being technically sound, fails to reach the market due to commercial hurdles [60]. By mapping QCRLs to QTRLs, stakeholders can better navigate this valley, as they gain insights not only about the technology's technical maturity but also its commercial viability at each stage of development. Such mapping supports informed decision-making and risk management. By understanding where technology sits in both the technical and commercial spectra, developers, investors, and policymakers can align their strategies and resources more effectively. They can anticipate potential technical and market barriers, prepare for regulatory requirements, validate their value proposition and business model, and determine optimal market entry strategies.

5. Quantum Readiness for Different Stakeholders

As quantum technology moves from the realm of theoretical research into the field of practical applications, it is essential to understand and foster a robust and effective quantum ecosystem. This ecosystem refers to the interconnected network of stakeholders, including researchers, industry practitioners, policymakers, educators, and investors, all contributing towards the development, adoption, and regulation of quantum technologies. A robust and effective ecosystem is the one that ensures a fluid exchange of knowledge and resources among its participants, facilitating continuous innovation, standardisation, and commercialisation of quantum technologies. It thrives on collaboration and mutual support, fostering perennial growth amidst market fluctuations and technological uncertainties. Participants in a robust quantum ecosystem are expected to assume distinct yet interconnected roles and responsibilities. Researchers, for instance, are tasked with advancing the scientific frontier of quantum technologies, while educators are responsible for cultivating a future-ready workforce equipped with quantum literacy. Industry practitioners transform theoretical research into market-ready solutions, continuously pushing the practical boundaries of quantum applications. Policymakers establish regulatory frameworks, balancing innovation, security, and ethical considerations. Lastly, investors provide the necessary financial resources, driving the ecosystem from early-stage research to commercially viable products. All these roles contribute to the vibrancy and resilience of the quantum ecosystem, each indispensable for fostering quantum readiness across different sectors. Hence, it becomes cardinal to understand the role of these stakeholders in quantum readiness. In the previous sections, we discussed the interpretation of quantum readiness and various models to assess current quantum readiness by using different models. Next, we describe in detail various perspective scenarios in which the term *quantum readiness* is predominantly used and of relevance for key stakeholders in the quantum ecosystem. We discuss what it means to be quantum-ready in each of these scenarios and its relevant indicators.

5.1 Government

Common themes for a government to be quantum-ready are to have the necessary infrastructure, expertise, and resources to develop, implement, and use quantum technologies. The following section outlines structures found across nations developing their quantum-readiness, namely strategies and roadmaps, ecosystem and supply chain, and ethics and policy.

National quantum strategies are a common framework for a government to identify areas where quantum technologies could have the most significant impact, such as in finance, healthcare, or national security. By focusing its investments [2] in these areas, a government can develop the necessary infrastructure and expertise to become a leader in quantum tech- nologies. A roadmap is essential to forecast the implementation of quantum technologies for each of the following points:

1. Research and development: Investment in basic research is essential for advancing the state of quantum technologies. This includes funding for universities, research institutes, and national labs to conduct basic research on quantum materials, devices, and systems.

2. Education and training: Investment in education and training programmes is critical to develop the workforce with the necessary skills and knowledge to design, develop, and implement quantum technologies.

3. Infrastructure: Investment in premises is essential to support the infrastructure and deployment of quantum technologies in specific industries or applications, including the development of testing and measurement facilities, as well as the establishment of quantum computing centres.

The development of coordinated local ecosystems and the understanding of supply chains are essential for quantum readiness. A secretariat sitting within a branch of the government is helpful to achieve several actions across the ecosystem, namely collaboration with stakeholders, coordination of resources, monitoring of implementation, engagement with international partners, public outreach, as well as regular updates and reviews. Such a collaborative approach is best practice to share expertise, resources, and to accelerate the development and adoption of quantum technologies. Such partnerships between the government, companies, research centres, and supporting organisations can ensure that the supply chain for quantum technologies is secure and resilient. Strategic development of domestic capabilities to produce quantum components, as well as their implementation in global supply chains, can accelerate commercialisation and improve supply chain resiliency. An outcome of a strategy is to help a government address the ethical and policy issues that can arise with the development and use of quantum technologies. This could include issues related to data privacy, cybersecurity, and the impact of quantum technologies on society. The implementation of standards and certifications for quantum components can ensure that they meet certain security and performance requirements, thus further enhancing the security and reliability of the supply chain. Standards and certifications, in particular, can help build public confidence by providing a benchmark against which the performance and security of quantum technologies can be measured. This can help alleviate concerns about the reliability and safety of quantum technologies, especially for applications such as healthcare, finance, and national security.

5.2 Industry

Industries, in the conversation about quantum readiness, play a pivotal role in the development and maturation of a quantum ecosystem. They should be key parts of strategies and influence governments to make structural and policy changes to attract other users. For a specific company, the journey to be quantum-ready could differ, mainly depending on the size of the company, or how the company embraces new technologies. Overall, the only way to become quantum-ready is by a step- by-step approach:

1. Firstly, understanding quantum is critical. For decision makers, an awareness of the foundations and basic principles of the technology in general terms will be sufficient, whereas more technical knowledge will be useful for technical professionals. Being aware of how the technology develops, as well as starting to get involved in the ecosystem is very important for any organisation. To start, a list of available resources can be found in Ref. [61].

2. Secondly, the understanding, at a high level, of how quantum technologies can be impacting the business is needed. At this point, most organisations identify an individual or a group of individuals who will take the lead on quantum readiness for the company. Building skills and awareness at this level is crucial.

3. At a later stage, companies will identify specific use cases and start with a proof of concept or a demonstrator, working with quantum startups. This early experimentation will bring a competitive advantage to the business [62]. As quantum technologies are overall in the early stages of development, and companies need to be patient, understanding the experiments and proof of concepts will need to be updated in the future.

4. Once companies are fully aware of the value and impact of the technology, a strategic roadmap will be developed, critical to making the business quantum-ready.

5. The mastering of the technology will come with a full implementation within the business.

End users are the ultimate beneficiaries of quantum technologies and their engagement is integral to shaping practical applications and driving market demand. They can play an important role in defining the use cases for quantum technologies.

Industries contribute to the quantum ecosystem by providing feedback and helping to fine-tune quantum technologies. As early adopters, they can trial quantum solutions, thereby identifying gaps, suggesting improvements, and ultimately aiding in the refinement and evolution of these technologies. Their feedback forms an iterative loop with developers, accelerating the maturity of quantum solutions. By participating in industry forums and public consultations, end users can help shape the discourse around regulatory standards, ethical guidelines, and future research priorities. It is also worth noting that engagement with industries needs to be a two-way street. Technologists and researchers need to understand the needs and constraints of end users, while end users need to be educated about the potential and limitations of quantum technologies. This mutual understanding can help to ensure that quantum technologies are developed in a way that is both innovative and practically beneficial. All in all, becoming quantum-ready for a business means taking full advantage of the technology.

5.3 Academia and skill-based institutions

Being quantum-ready involves a combination of both theoretical knowledge and practical skills needed to work in the rapidly evolving field of quantum technologies.

Academic institutions can play an important role in filling the gaps needed to be quantum-ready by providing individuals with the foundational knowledge and transferable skills through specialised academic programmes, conducting research, partnering with industry for hands-on training, providing experiential learning opportunities, and offering continuing education programmes.

While it may be challenging for academic programmes to have enough resources to make students fully qualified for quantum careers, many programmes are taking steps to address this challenge and ensure that their students are well-prepared for the demands of the field. For example, some universities and colleges are establishing dedicated quantum computing centres, institutes, and labs to provide students with access to state-of-the-art equipment and resources [63–65]. These centres often work closely with industry partners to ensure that students are gaining the skills and knowledge that are most in demand in the field.

An increasing number of academic stakeholders and associations worldwide are starting to create and include specialised courses in quantum technologies within the syllabus of interdisciplinary programmes and degrees.

To create a diverse quantum workforce and mitigate potential biases in quantum technologies, academic programmes need to attract individuals from underrepresented groups to fields, such as computer science, math, statistics, physics, material science, and chemistry. These efforts should begin early, with K-12 interventions that offer exposure to quantum technologies and make them accessible to all students. Partnering with online learning platforms and skill-based training institutions can be another way for academic institutions to provide students with access to a broader range of resources and expertise [66, 67]. Programmes like *Qubit by Qubit* have seen successful in increasing interest and participation in quantum computing among middle and high school students from diverse backgrounds [68]. Universities also have a crucial role in building a talent pipeline by offering courses, programmes, and research opportunities that provide students with the necessary skills and knowledge to pursue quantum careers. In addition, business leaders can influence the shift towards quantum learning in schools and universities by demonstrating the importance of this field through corporate involvement. Ultimately, academic programmes must work to create a pathway for the talent pipeline by removing barriers to entry and ensuring that all students have access to resources and opportunities to develop quantum-ready skills [61].

The field of quantum technologies requires a diverse workforce to meet its needs. However, STEM disciplines still face challenges in broadening participation, particularly among women and underrepresented racial and ethnic groups. Academic programmes must address the barriers that currently exist and provide support, mentorship, and recognition for diverse perspectives and expertise, to increase accessibility to students and to promote inclusivity and diversity [69].

5.4 Readiness with respect to ethics and protocols

Until this section, a general framework for quantum readiness and the elaboration for different stakeholders have been provided. Being quantum-ready involves several factors, including the availability of quantum hardware and software, the expertise of personnel, and the quality of the infrastructure. To be quantum-ready, an organisation must have access to the necessary technology, personnel, and infrastructure. However, this narrow concept of quantum readiness can, and sometimes should, be expanded to cover any ethical and legal aspects, especially following the national and international protocols, such as those on standardisation.

Being quantum-ready is an important step for organisations that are considering the use of quantum technologies. It allows organisations to identify and address any challenges or limitations that may prevent them from effectively using quantum technologies. For example, an organisation that is not quantum-ready may lack the necessary hardware, software, expertise, or infrastructure to effectively use quantum technologies. In order to be quantum-ready, an organisation must invest in quantum technologies, by developing new algorithms and/or applications, training personnel, and building a quantum-safe infrastructure.

Investing in quantum readiness is a significant undertaking and requires a long-term commitment to preparing for the use of quantum technologies. It is not something that can be done quickly or easily. However, the benefits of being quantum-ready are significant. Organisations that are quantum-ready will be able to take advantage of the potential benefits of quantum technologies and will be well-positioned to compete in the emerging quantum global economy. Companies, governments, NGOs, and other stakeholders must be quantum-ready because quantum technologies promise some essentially different capabilities. To take advantage of the benefits of quantum technologies, organisations must be prepared to use them effectively. However, quantum technologies raise many ethical concerns, including the potential misuse of technology, its impact on jobs and the economy, unequal access to technology, and its potential impact on society.

As one well-known example, quantum technologies could be used for malicious purposes such as hacking and espionage, which highlights the need for appropriate safeguards and regulations [70]. This directly impacts the meaning of quantum readiness. Additionally, the use of quantum computing could automatise specific tasks, potentially leading to job losses in certain industries. This raises concerns about the potential for economic disruption and the need for policies to support affected workers and sectors. One can argue whether being quantum-ready also encompasses being ready against such disruptions brought forth by this new and emerging set of technologies. Furthermore, only certain individuals or organisations may have access to mature quantum technologies [71], leading to potentially increasing inequalities and disparities. This raises concerns about fairness and equitable access to the benefits of quantum technologies and the need for policies to ensure that the technology is accessible to all. Finally, there are also concerns about the potential impact of quantum technologies on different stakeholder groups in society [72], and the need for careful and deliberate planning to ensure that quantum technologies can be used ethically and beneficially.

There are many discussions and a growing literature on ethical and societal responsible use of quantum technologies ranging from arguments on the democratisation of quantum technologies [73] to calls for not even building quantum computers at all [74]. In practical terms, these discussions inform organisations, governments and the public, and could change the stakeholders' perception of quantum technologies. For example, the topic of trust is discussed openly in a Time article [75], where it was proposed that '…soon will come a time when trusting a quantum computer will require a leap of faith', and without trust-building across the entire ecosystem, there will be strong hesitancy to take this leap of faith. There are efforts to mitigate this hesitancy and widely accepted ethical guidelines and protocols are established methods of trust-building in new and emerging technology ecosystems.

To employ methods of trust-building, one needs to frame the object of this trust, in this case, quantum technologies. It is discussed in the literature that quantum technologies can be considered system technologies with a systemic impact on society [76], which calls for an anticipatory approach. Similarly, arguing for a strong *Responsible Research and Innovation* (RRI) approach can also be found in the literature [77]. There is even a call for action from some industry partners and different stakeholders in the ecosystem for the ethical development of these technologies [78]. There are also many proposals and important highlights in the literature on arguing for further understandability of the quantum theory [79], the effects of hype on teaching about quantum technologies [80], introducing ethics into quantum information classrooms [81], awareness raising as the bare minimum that should be done [82], and many other potential actions to prevent quantum technologies running into fiascos of implementation at the interface of science and society [83]. One might consider how these discussions can be practically tied to an organisation's quantum readiness. A clear example of this is the White House memorandum *on Promoting United States Leadership in Quantum Computing While Mitigating Risk to Vulnerable Cryptographic Systems*, which prioritises '…the timely and equitable transition of cryptographic systems to quantum- resistant cryptography, with the goal of mitigating as much of the quantum risk as is feasible by 2035' [84]. For those who have been following the discussions on the quantum threat [70], this came as no surprise. It is the poster child case of the potential of future quantum technologies causing a massive impact on today's regulatory landscape. It might seem like this was always supposed to happen, but the chances of this becoming a regulation, let alone a company fundraising $500 million on this particular topic was negligible just a decade ago [85]. Furthermore, this is a particular example of how the values and priorities of certain stakeholders in the ecosystem can cause major shifts in not only the narratives but also the regulatory and opportunity landscape of an entire industry with consequences far-reaching into almost all industries.

There are many moving parts on the regulatory landscape both in early and late stage standardisation efforts such as the Quantum Internet Research Group [86] under the Internet Engineering Task Force working on the future standards of the quantum internet while others such as *European Telecommunications Standards Institute* (ETSI) *Industry Specification Group* (ISG) working on QKD standards [87], which has an impact on industrial relations much sooner. Ethics plays an important role in these processes. Different stakeholders have different value

sets and even within the stakeholder groups with similar value sets, there are differences in prioritisation of these. There are some promoting global open access and sustainability while not explicitly for democratic values due to geopolitical concerns, while others that argue strongly for democratisation may find themselves only arguing for it in a limited context of like-minded countries. Discussions on export controls and even controls on knowledge transfer are common practices in the ethical and regulatory context of quantum technologies.

As discussed earlier in this article, techno-economic paradigms are characterised by a set of shared beliefs, values, and practices that define the boundaries of what is considered technically feasible and economically viable [36], but in a wider context, these also need to be societal acceptable [35] to fully become system technologies [76]. Hence, organisations aiming for quantum readiness should keep track and maybe even actively participate in these discussions on what should be the wider set of values and protocols surrounding how these technologies interface with the market and the whole of society [83].

5.5 People and society

People and society play pivotal roles in shaping and sustaining the quantum ecosystem [88]. Beyond education, the public dialogue and consensus-building processes are crucial to address the ethical, legal, and societal implications of quantum technologies. Quantum cryptography's effects on data privacy, the implications of quantum computing on job security and new forms of employment, and other such considerations should be widely and openly discussed. From a societal perspective, fostering an environment that encourages innovation and entrepreneurship in quantum technologies is crucial. Policymakers, guided by public sentiment and expert advice, have a critical role in shaping regulations that will determine how quantum technologies are used, ensuring their alignment with societal values and norms. As we explore the role of end users in promoting and normalising the adoption of quantum technologies, it becomes evident that their experiences and testimonials can be of considerable value in inspiring confidence and interest in other potential users and significantly influence the widespread adoption of quantum technologies through their advocacy and normalisation efforts. Nurturing a robust and effective quantum ecosystem is a collective endeavour that demands the synchronised efforts of diverse stakeholders. As quantum technology transcends the borders of academia and finds its footing in various industries, it is incumbent upon all participants to fulfil their roles conscientiously. Researchers, educators, industry practitioners, policymakers, and investors all bear the mantle of responsibility to shape a quantum-ready future. As we stand on the cusp of this second quantum revolution, it becomes crucial to leverage the power of this integrated ecosystem to transform the theoretical potential of quantum technology into tangible benefits for society at large.

6. Conclusion

Quantum readiness refers to the state of being equipped to adopt and utilise quantum technology, providing organisations and nations with the potential to secure a first-mover advantage, shape the technology's future direction, attain a competitive edge, and achieve

economic prosperity. This paper highlights the importance of quantum readiness, along with innovation models and assessment tools that enable individuals, organisations, and businesses to evaluate their quantum readiness and formulate strategies for becoming quantum-ready.

We started with the classification of emerging technologies based on their level of maturity and potential impact which provides a useful framework for policymakers and business leaders to understand and prepare for the impact of these technologies on their respective industries. Disruptive technologies have the potential to create entirely new markets or disrupt existing ones while enabling technologies facilitate the development of new goods, services, or business models. Sustaining technologies, on the other hand, improve the performance of existing products or services without necessarily creating new markets or disrupting existing ones. Quantum technology is an emerging disruptive technology that represents a significant departure from traditional classical technologies and has the potential to revolutionise various industries. Policymakers and business leaders can position themselves to benefit from the potential of quantum technology by proactively identifying potential disruptions, determining areas for research and development, and informing policy decisions.

In the third section, we addressed the need to understand quantum readiness. It is anticipated that the rapidly advancing quantum technology will disrupt various industry sectors, revolutionise cryptography, improve cybersecurity, and accelerate scientific research. Countries and organisations that invest in and embrace quantum technology will have a significant competitive advantage, while those that do not may fall behind. Quantum readiness is crucial for businesses and governments to thrive in the future, and addressing this issue re- quires time, research and development investments, skilled human resources, and strategic decisions. Quantum technology shares characteristics with *General-Purpose Technologies* (GPTs), which have a long-term impact on the economy and society. Therefore, organisations can ensure their competitiveness and economic prosperity by collaborating to build a strong quantum ecosystem and embracing quantum technology.

We formalised the *Quantum Technology Readiness Levels* (QTRLs), their descriptions, and expected outcomes on the basis of which we assessed the current status of different quantum technologies. We also established a time horizon indicating the anticipated date by which these technologies will be successfully adopted and deployed for practical applications. Unsurprisingly, quantum computing is still in its infancy; by contrast, quantum sensing and communications can be considered to be in more advanced stages.

We then introduced Quantum Commercial Readiness Levels (QCRLs) as a complementary framework to QTRLs. By doing so, we not only address the technical maturity of quantum technologies but also their market readiness and commercial viability. Furthermore, we have explored the process of mapping QCRLs to QTRLs. This brings a necessary cohesion between the technical progression and market readiness of quantum technology.

Finally, we discussed the significance of quantum readiness for key ecosystem stakeholders and defined relevant indicators to be quantum-ready.

1. Governments need to establish infrastructure, allocate resources, and develop expertise to become quantum-ready. National quantum strategies and roadmaps can assist in identifying priority innovation areas for investment. An effective local ecosystem is also important, requiring partnerships with businesses, research institutions, and supporting organisations to ensure a secure and robust supply chain. To address ethical and policy challenges, governments must implement standards and certifications to ensure the security and reliability of quantum technologies.

2. The process of becoming quantum-ready for a company depends on its size and its willingness to embrace new technologies. The approach involves first understanding the basics of quantum technology and getting involved in the ecosystem by utilising available resources. At a later stage, identifying use cases and experimenting with proof of concept with quantum startups brings a competitive advantage to the business. Once the company comprehends the benefits of the technology, a strategic roadmap is established for complete integration within the business. Proficiency in the technology ultimately enables the company to harness its full potential.

3. The development of a quantum workforce with foundational knowledge and transferable skills required for the rapidly evolving field of quantum technologies can be facilitated by academic and skill-based institutions through specialised academic programmes, research, hands-on training, experiential learning opportunities, and continuing education programmes. To promote inclusivity and diversity, academic programmes must target individuals from underrepresented groups in fields such as computer science, math, statistics, physics, material science, and chemistry, beginning with K-12 interventions. Additionally, academic institutions need to establish a pathway for the talent pipeline by removing barriers to entry and providing resources and opportunities for students to acquire quantum-ready skills. To increase accessibility and inclusivity, academic programmes must address the barriers that currently exist and provide support, mentorship, and recognition for diverse perspectives and expertise.

4. The benefits of being quantum-ready are significant, allowing organisations to take advantage of the potential benefits of quantum technologies and be well-positioned to compete in the emerging quantum global economy. However, there are also ethical and legal aspects to consider, and organisations must follow national and international protocols, such as those on standardisation. Quantum technologies may also raise ethical concerns, including potential misuse, impact on jobs and the economy, unequal access to technology, and its impact on society. There is growing attention towards the ethical and societal responsible use of quantum technologies, ranging from arguments on the democratisation of quantum technologies to calls for not building quantum computers at all. To employ methods of trust-building, organisations need to frame the object of this trust, in this case, quantum technologies, and take an anticipatory approach. Furthermore, there is a growing need for a call for action from industry partners and different stakeholders in the ecosystem to take into account the ethical and societal concerns to effectively use quantum technologies.

In the coming years, the quantum technology sector is expected to undergo significant changes. Some technologies will become operational, while others may not succeed due to challenges in engineering or commercialisation. It is not possible to make precise predictions about which technologies will succeed or fail. However, adopting a forward-looking approach can help organisations or individuals become quantum-ready.

Author Contributions

Abhishek Purohit: Data curation; formal analysis; investiga- tion; methodology; resources; validation; visualisation; writing – original draft; writing – review & editing. **Maninder Kaur**: Conceptualisation; formal analysis; methodology; project administration; resources; supervision; validation; writing – original draft; writing – review & editing. **Zeki Can Seskir**: Conceptualisation; formal analysis; investigation; methodology; validation; writing – original draft; writing – review & editing. **Matthew T. Posner**: Formal analysis; investigation; writing – review & editing. **Araceli Venegas-Gomez**: Investigation; resources; supervision; validation; writing – review & editing.

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Conflict of Interest Statement

The authors whose names are listed above certify that they have NO affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Article 1.5: Quantum games and interactive tools for quantum technologies outreach and education[90]

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Abstract. We provide an extensive overview of a wide range of quantum games and interactive tools that have been employed by the quantum community in recent years. We present selected tools as described by their developers, including “Hello Quantum, Hello Qiskit, Particle in a Box, Psi and Delta, QPlayLearn, Virtual Lab by Quantum Flytrap, Quantum Odyssey, ScienceAtHome, and the Virtual Quantum Optics Laboratory.” In

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addition, we present events for quantum game development: hackathons, game jams, and semester projects. Furthermore, we discuss the Quantum Technologies Education for Everyone (QUTE4E) pilot project, which illustrates an effective integration of these interactive tools with quantum outreach and education activities. Finally, we aim at providing guidelines for incorporating quantum games and inter- active tools in pedagogic materials to make quantum technologies more accessible for a wider population.

Keywords: quantum games; quantum tools; quantum education; education; interactive tools; storytelling.

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1.Introduction

The second quantum revolution[1] has been unfolding for over two decades, and numerous countries across the globe acknowledge the potential of these technologies. In the last decade, more than 15 publicly supported national initiatives were launched, with several of them having budgets exceeding billion euros, particularly in the UK,[2] the US,[3] the EU,[4] France,[5] Germany,[6] India,[7] and China.[8] Both the number of new publications per year[9] and the number of patents[10] granted on quantum technologies (QT) have been climbing steadily for the last decade, along with the growing number of start-ups and renowned companies getting into the field. Recently, the field has been receiving attention from private funding sources, which some have been referring to as the 'quantum gold rush.'[11] Within two decades, QT has advanced from a topic that was mainly discussed in physics conferences to becoming a strong contender for a potential future industry.

The developments in QT, similar to most emerging technologies, bring several social and technical challenges. First and foremost, for the general public, QT is still an abstract concept with limited accessible materials on the topic.[12] However, there is an urgency to make QT accessible to lay audiences and facilitate the stakeholders' inclusion into the debate on the subject.[13] Second, the growing advancements in the industry require a rapid expansion of the workforce[14] and an increased level of understanding of QT in educational, business, and policy-making efforts. Finally, similar to most promising emerging technologies, QT is expected to impact society profoundly;[15] however, this may cause preexisting divides on national and international levels to grow wider. These concerns encourage some members of the quantum community to adopt a responsible approach[16] and build a common language.[17]

One of the most important steps taken toward addressing these concerns is increasing public engagement and involvement in QT. The predominant ideas in the existing literature are on increasing quantum literacy at the K-12 and general public[18] levels and focusing more on education and developing transdisciplinary problem-solving skills.[19] Therefore, education and outreach activities are of paramount importance in promoting QT and making it accessible for a wider audience, engaging all potential stakeholders.

The literature on QT and its "social" impact has expanded significantly,[20] and stakeholders' engagement in QT is rapidly increasing; therefore, numerous initiatives are being set forth to address these growing demands. There are several coordinated efforts around the world, such as the QT education coordination and support action for the EU's Quantum Flagship (QTEdu CSA),[21] the Q-12 Education Partnership in the US,[22] and the IEEE Quantum Education[23] initiative. In addition to organizing extracurricular activities, these initiatives also focus on identifying and improving the potential tools that can be utilized by quantum outreach and education practitioners. In this respect, learning quantum concepts through games has gained prominence as an approach to benefit the quantum community at large and support these outreach and education efforts extensively. For example, quantum games are a key means of engaging students and teachers, making up four out of five of the Q-12 Education Partnership's QuanTime K-12 classroom activities.[24] The quantum games are used here to refer to computer (or video) games with one or more of the phenomena from quantum physics embedded in their game mechanics —note that this is not (in principle) related to research efforts extending game theory to include quantum mechanics.[25,26]

The development of science-based games can set out to achieve a variety of goals, including for educational purposes, citizen-science-based[27] research purposes, science outreach and public engagement, and/or fun. Games are unique among other tools for research and education in that, if they are widely adopted, they have the potential to reach audiences beyond most coordination efforts, and thus they can be useful vectors for increasing quantum awareness. This is important for two reasons. First, it is beneficial that the goal of understanding the science targets not only current and future technical experts on the topic but also people with other occupations and skills who will transform the science into technologies impacting many other areas. Equally important is the learner gaining exposure to a new concept, thereby making the concept less intimidating when reencountered. This is especially impactful to learners from underrepresented or disadvantaged backgrounds who have less opportunities or encouragement to experience this topic in the first place, helping them to succeed in the field utilizing their skills and perspectives.

In this article, we introduce a wide range of tools that have been tested by developers and used by the community for several years. We present different approaches and tools, together with the experiences of their developers, aiming to provide current and future practitioners of quantum outreach and education activities a better understanding of their application and extent. Most of the authors are members of the pilot project Quantum Technologies Education for Everyone[28] (QUTE4E) organized under the Quantum Technology Education Coordination and Support Action (QTEdu CSA) of the EU's Quantum Flagship program. Therefore, the list of games and interactive tools provided here consists of a non-exhaustive but representative list. Further information on the pilot project can be found in Sec. 5.

The article is formatted in the following manner. In Sec. 2, we argue for the importance of photonics in QT outreach and education efforts. In Sec. 3, we discuss the relationship between science-based games and quantum games,[29] including a brief discussion on the evaluation of quantum games. In Sec. 4, Secs. 4.1–4.7 are dedicated to introducing quantum games and

interactive tools for QT outreach and education, and in Sec. 4.8 we explore some activities in creating quantum games. Finally, in Sec. 5, a more detailed description of the pilot project QUTE4E is given.

2.Locating Photonics in QT Outreach and Education

To understand QT—such as quantum cryptography, quantum computing, or quantum sensing—a knowledge of the quantum phenomena that they rely on is essential. These relevant quantum concepts include superposition, entanglement, interference, dynamical evolution, and measurement,[30–33] and there is an emerging literature introducing these through optics concepts.[34–38]

Using qubits allows us to discuss quantum information without relating it to physics.[39] Although this adds simplicity in some respects, it also results in challenges. First, all current quantum devices are deeply rooted in physics. For now, to use them efficiently, we need to consider which operations are physically possible. Second, quite a few phenomena are easier to explain with concrete systems. This offers a direct way to visualize them and relate them to the broader fields of wave physics, electrodynamics, and optical communications.

Introductions that aim to be entry-level usually use electron spin[40] or photon polarization[41] to introduce quantum mechanics. Arguably[42] photon polarization is an easier two-level system that translates to demonstrable experiments with classical light and behaves more intuitively with rotations and superposition.

Quantum mechanics is known to be prone to misconceptions, resulting from otherwise well-intentioned physicists, teachers, and science communicators.[43] Misconceptions are common even among students of physics.[44,45] A common problem with teaching quantum mechanics lies in training students to distinguish the phase of a superposition. Telling someone that it is possible to have a qubit in the $|0\rangle$ and $|1\rangle$ state simultaneously leaves no such space and fails to distinguish between statistical uncertainty and quantum mechanics, as explained by Scott Aaronson.[46]

> *Over the years, I've developed what I call the Minus-Sign Test, a reliable way to rate popularizations of quantum mechanics. To pass the Minus-Sign Test, all a popularization needs to do is mention the minus signs: i.e., interference between positive and negative amplitudes, the defining feature of quantum mechanics, the thing that makes it different from classical probability theory, the reason why we can't say Schrödinger's cat is "really either dead or alive," and we simply don't know which one, the reason why the entangled particles can't have just agreed in advance that one would spin up and the other would spin down.*

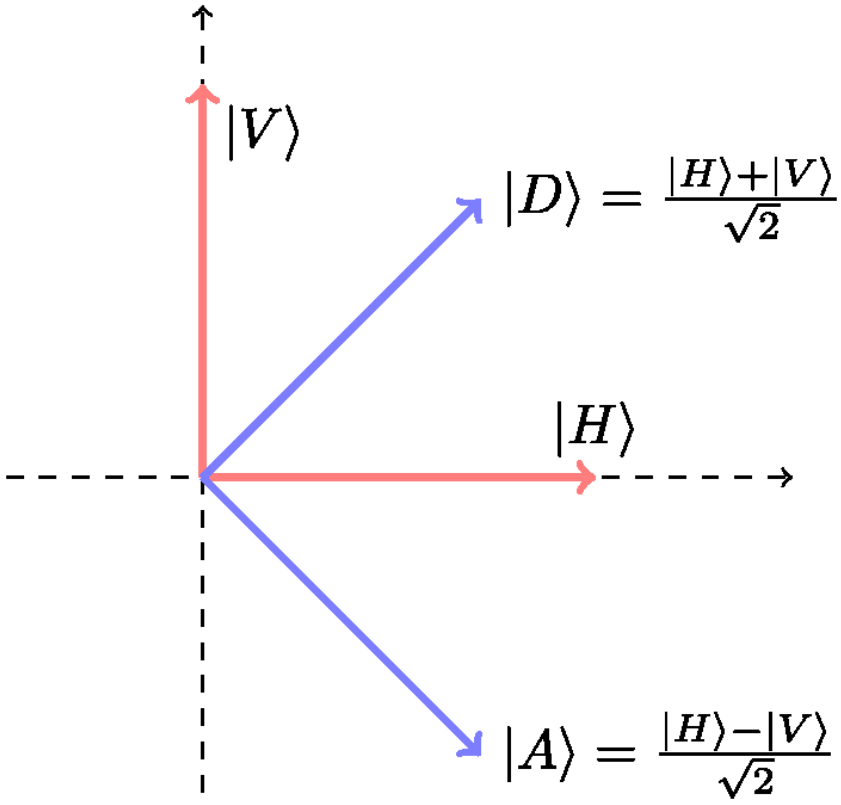


Fig. 1 Polarization of light offers a straightforward way to present orthogonal states. With a typical mapping |H⟩ = |0⟩ and |V⟩ = |1⟩, quantum states (|0⟩ ± |1⟩)/√2 have a direct physical representation, both easily demonstrable experimentally in a class and matching the high-school definition of orthogonality.

However, photon polarization gives a quick way to distinguish such states and to show that they are orthogonal (see Fig. 1).

Moreover, such systems give an easy way to explain measurements (with linear polarization filters known in photography and LCD screens, followed by detectors known from cameras), translate back and forth with nonlocal superposition over different paths (via polarizing beam splitters), and relate to simpler and laboratory-demonstrable experiments with interference. In addition, several quantum communication protocols were first demonstrated with photons. These include quantum key distribution with BB84[47] and Ekert[48] protocols, the Bell inequality violation,[49,50] and boson sampling.[51]

Photonic systems can be easily extended to more advanced systems. For example, to encode qudits (quantum systems with d levels, typically $d > 2$), one uses different spatial modes and angular momentum, giving rise to qualitatively different classes of entanglement than that achievable with qubits.[52] Photonics can also be used to simulate molecular vibrations and dynamics.[53]

At the same time, it is crucial to underline that there are many other physical implementations of quantum technologies—involving spin, energy levels, and currents in superconducting loops, among others. We believe that, to teach modern quantum technologies, we need to show phenomena from different angles—both physical and abstract. The same core properties of quantum mechanics are important regardless of which system we study, yet some may be better to explain a given phenomenon or more easily relatable to currently available quantum devices and protocols. Hence, we present a wide array of quantum games and quantum interactive tools, each approaching from various angles, underlying various phenomena.

It should also be noted that there is an emerging literature on introducing quantum technologies (especially quantum computation) through computer science,[54–56] programming[57–60] oriented, and visually oriented (no-math) approaches[19,61–63] in parallel to the physics-focused approaches. All of these can be thought of as efforts in further developing the outreach and education landscape of quantum technologies.

3.Quantum Games and Interactive Tools as Novel Methods for QT Outreach and Education

We believe that learning the basic concepts of quantum physics and quantum information science should be made accessible to the public regardless of background to understand the significance of the second quantum revolution,[13] and anyone regardless of their background can access the tools to learn and develop quantum technologies. A number of resources are available,[64] but understanding requires that the learning be sequential:[65] quantum computing and algorithms need prior understanding of qubits, quantum gates, and so on. Games are a natural way for pacing the progression through which learners may grasp these concepts. Efforts are needed to establish dissemination channels to reach a broader audience, and games can serve the purpose with their popularity across society.

The interdisciplinary nature of QTs leads to a diverse range of skills that the quantum workforce should possess;[14] thus it should include people from different backgrounds. This poses a particular challenge: teaching quantum mechanics is daunting to teachers for whom this is also a new topic. Virtual labs and learning tools, accompanied by explanations of the simulated physics, are cost-effective environments for exploring and building intuition of quantum phenomena.

The connection between interactive storytelling and quantum computing was briefly explored in the literature.[66] However, a comprehensive discussion on why and how these tools can be utilized for education and outreach purposes has not been made. We provide the groundwork for such a discussion by providing a quick introduction to science-based (Sec. 3.2) and serious (Sec. 4) games, followed by a description of quantum games and interactive tools from their developers (Secs. 4.1–4.7).

In this section, we cover four topics. We discuss in Sec. 3.1 early and current quantum tools, the former being precursors of today's quantum games and interactive tools. In Sec. 3.2, we

briefly discuss the wider arena of science-based games, with its increase in number and success being a valuable witness of the general trend and an inspiration. Section 3.3 illustrates explorable explanations as an example of how enhanced interactivity can play a practical role in science communication. Finally, in Sec. 3.4, we discuss the challenge of evaluating quantum games, providing suggestions for necessary future work.

3.1.Interactive Tools

A number of different computer-based quantum tools have been developed for educational purposes. Typically, these tools are geared toward the visualization of quantum phenomena. Early efforts by the Consortium for Upper Level Physics Software released quantum visualization software packages in the mid-1990s;[67,68] some of the authors of these software packages also released a book on quantum mechanics simulation.[67] Later efforts included a series of books by Thaller[69,70] and Zollman et al.[71]

In the early 2000s, Paul Falstad released a series of Java applets simulating physics,[72] including 12 on quantum mechanics and many others on waves physics. In particular, the one-dimensional quantum mechanics applet allows one to draw any potential and any wavefunction, as well as explore the position space, momentum space, energies, and eigenstates simultaneously (Fig. 2). The ripple tank applet allows for the exploration of interference—crucial for both classical wave physics and quantum phenomena. Unlike other simulations, a user can draw the interference setup in a sandbox mode. Paul Falstad's applets gained enough popularity to be ported as mobile apps and rewritten in JavaScript to be usable with modern browsers.

Other web-based applications include the Physlet simulations[74] and a set of simulations developed by Joffre.[75] The ubiquitous PhET simulations[76] have developed a set of quantum-specific simulations; PhET researchers have published a wide array of research on the design and use of their simulation.[77–80] Other such research-validated quantum simulation tools include the QuILTs[81] developed at the University of Pittsburgh,[82] the QuViS tutorials[83] developed at St. Andrew's University,[84,85] and the Quantum Composer simulation tool[86] developed at Aarhus University,[87,88] which is described in more detail later in this paper.

With the exception of the node-based programming in Quantum Composer, the tools developed here are typically set modules exploring a specific quantum phenomenon (sometimes including supplementary material that instructors can use to develop exercises), and interactive tools (e.g., the PhET, QuViS, and QuILT simulations) allow students to easily modify parameters and explore the simulation in more detail. However, none of these tools can be classified as games as they lack the required elements in the interface and design that engage the students outside their traditional educational goals. In Sec. 4, we explore more recent and ongoing efforts in accomplishing this task, but first, we introduce the concept of science-based games and explorable explanations as an example.

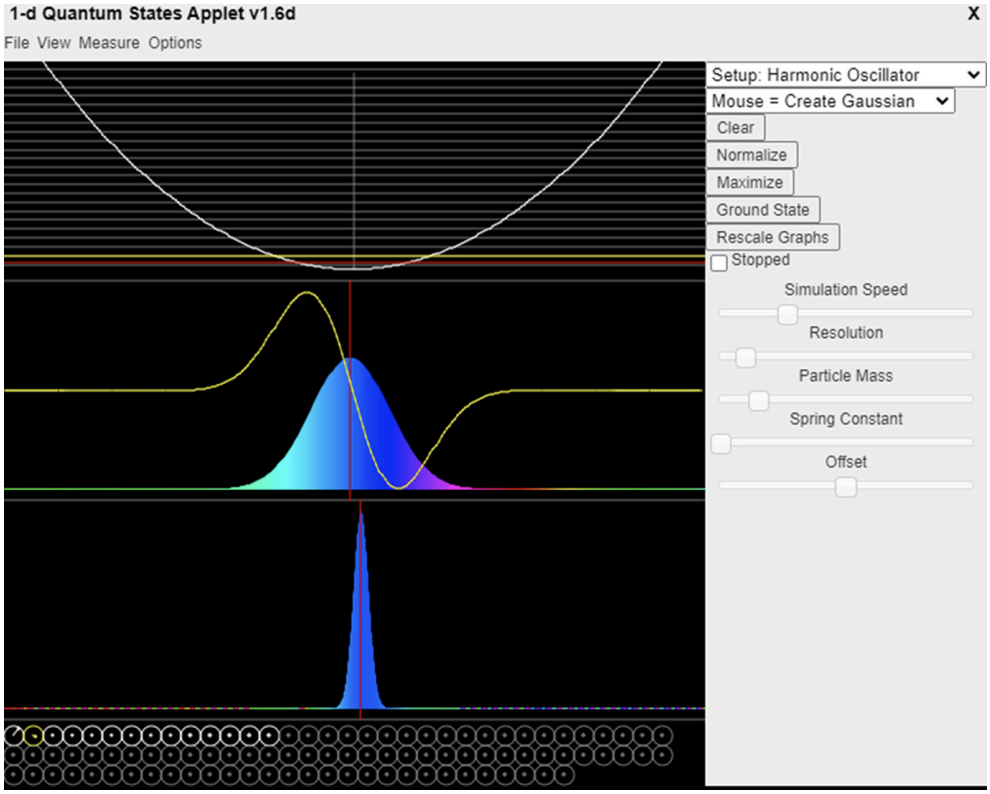


Fig. 2 1-D quantum mechanics applet (a single-particle quantum mechanics states in one dimension) by Paul Falstad.[73] An early simulation gives a user the ability to simultaneously see (and edit): 1-D potential, eigenstates with eigenenergies, wavefunction as a function of position and time, wavefunction as a function of momentum, and relative amplitudes of each eigenstate.

3.2.Science-Based Games

The traditional way of teaching includes textbooks, lectures, and projects. This teaching method is performed top-down, with clear instructions and expectations. Students are tested via grading of projects, homework assignments, and exams. Usually fun, or the ability to explore on one's own, is not the key focus. Often students' motivation is extrinsic—to pass a course with a good grade. These activities can be gamified, provided with supplementary goals, scores, and challenges to make them more engaging.

In contrast, science-based games[29] approach teaching from the opposite direction: to primarily focus on creating an experience sparking intrinsic motivation,[89] that is, students play for fun, but learn in the process, as their gaming experience requires learning concepts to proceed or provides an explorative pathway through the game that promotes learning[90] (even if it is not strictly necessary).

There are several existing games showing different aspects of physics—special relativity theory,[91] electromagnetism,[92] classical physics, and orbital mechanics.[93] There are games that teach computing—creating circuits from the simplest blocks—NAND gates[94] and low-level

programming in assembly. Although a lot of games are standalone one-off projects, some game developers specialize in science-based games, e.g., Zachtronics (algorithmics) and Test Tube Games (physics). Some science-based games go way beyond the niche – SpaceChem and Kerbal Space Program sold over 1 million and over 2 million copies on Steam,[95] respectively.

3.3.Explorable Explanations

Explorable explanations[96] (or "explorables") come at educational games from the opposite direction: instead of "games, but with science communication added," they are "science communication, but with interactivity added," although we should note that interactivity is a necessary but not sufficient condition for something to be considered a game. Most explorables are educational articles, with embedded simulations instead of static media such as images and videos. The term "explorable explanation" was coined in 2011 by interaction designer Bret Victor,[97] with an ambitious goal of creating a two-way communication between the author and the reader. With an open-ended creative environment, readers can challenge the author's assumptions by going beyond what the author ever imagined. This ambition is explained more in the 2019 essay[98] by former Khan Academy designer Andy Matuschak and quantum physicist Michael Nielsen. These approaches are tightly related to exploring new visual languages of communication (see Fig. 3).

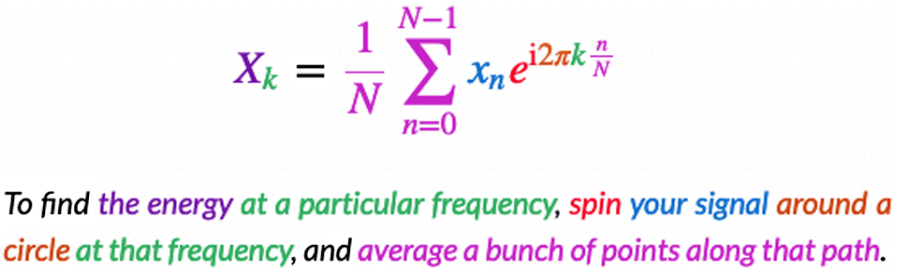


Fig. 3 A self-descriptive formula of the discrete Fourier transform: a web-based MathJax implementation[99] of an equation color-coding scheme designed by Stuart Riffle from 2011.[100] Earlier approaches of color-coding go back to the Byrne's Euclid from 1847[101] subtitled "In which Coloured Diagrams and Symbols are Used Instead of Letters for the Greater Ease of Learners."

Deep learning shares many similar concepts with QT—both hyped, fast-growing technologies, are heavily based on linear algebra with tensor products and have a nontrivial entry barrier. The abundance of online tools that help users to learn and directly use deep learning already gets traction in gaming[102] and can provide guidance on how to present quantum technologies in an accessible, ready-to-use way. There are already numerous explorable explanations in machine learning and AI,[103] including general introductions to probability and statistics,[104] decision trees and validation in machine learning,[105] training of artificial neural network classifiers,[106] and interpretability of convolutional neural networks.[107,108] In 2016 to 2021, a

dedicated peer-reviewed journal Distill aimed at providing interactive explanations of novel research.[109]

Although the interactive environment of Jupyter Notebooks is a standard way of providing introductions to quantum software frameworks,[110,111] there is only a handful of other quantum explorable explanations, e.g., a spaced-repetition-based introduction to quantum computing,[112] an introduction to quantum Fourier transform,[113] and an exploration of single-qubit gates.[114]

3.4.Evaluation of Quantum Games

A common question when considering any tool is whether it truly works as intended, and quantum games are no exceptions. Currently, neither common design methodology[115] nor universal evaluation tools for quantum games are available. This is largely due to fragmented game-development processes[116] (i.e., by professionals, by university researchers, or in hackathons) and the diverse game goals (i.e., research, education, outreach, and/or fun). Indeed, some of the games described in Sec. 4 have been evaluated individually. For example, the developers of Quantum Moves 2, with its focus on citizen science, published their results in a peer-reviewed journal.[117] Similarly, the games Particle in a Box[61] and the Quantum Odyssey[118] have articles published in peer-reviewed journals containing evaluation sections. However, a proper and comprehensive evaluation and assessment scheme that can be applied to a variety of quantum games is missing in the literature. Validation of these quantum games, especially when ensuring that educational games serve to teach students relevant concepts, is important and should be further developed as activities in the field are progressing. Although the development and discussion of a universal quantum game evaluation tool is beyond the scope of this paper, we offer some suggestions here.

First, we need to categorize quantum games in terms of their basic information such as on which platform they run and their licenses, their types, and the concepts that they are drawing upon. Efforts to do this are underway,[116] but the task difficulty grows with the impressive growth rate of the quantum games landscape and with the rate at which games become obsolete because of, e.g., operating-system compatibility and security or operating system development leading to the acquisition of game-breaking bugs. We believe that it could be useful to develop a quantum games version of Physport,[119] which is a repository of research-based recommendations, assessments, tools, and practices for physics education, where games can be rated. For example, the Force Concept Inventory[120] received a gold star rating from Physport for its extensive research-based evaluation.

In parallel, researchers should work to develop best practices for the evaluation of quantum games (similar to those developed for quantum software[121]), focusing on the common goals of research, education, and fun; these best practices can be collected in the same repository as the games themselves. Also, within the repository, we can denote whether the game is being actively developed, is in a usable state, or has been deprecated in some way. This can be an invaluable tool for tracking how quantum games, their goals, and their use cases change over time.

Evaluating the effectiveness and efficiency of a video game for education requires a number of steps,[122] which as a pilot we are completing. To start with, we need to work out a storytelling format, in which the use of the purpose of the quantum game or interactive tool is made explicit. This has been the subject of theoretical work introducing the concept of culture-scientific storytelling with special attention to quantum science and technologies,[123] which is being tested in outreach events such as the workshops devoted to high-school students around the Quantum Jungle interactive installation.[122] Then, suitable evaluation tools must be designed in correspondence with on-purpose didactic experiments. For example, in one such experiment performed in a high school in Treviso (Italy), the Quantum TiqTaqToe video game was used as a central tool in a highly compact didactic intervention lasting just two afternoons (including a TiqTaqToe tournament) to educate students on the concepts of quantum state and measurement, quantum superposition, and entanglement.[124] Suitable evaluation tools in the form of questionnaires were designed for this purpose and analyzed; they showed a high degree of effectiveness of the quantum game in supporting the students' ability to develop an operational understanding of the aforementioned concepts.[124] Although much systematic research needs to be performed along similar directions, these first steps appear quite promising and encouraging. A preliminary effort to categorize the games presented in our paper is provided in Table 1.

Table 1 A summary of games presented in Sec. 4.

Title	Initial release	Platform	License	Type	Key concetp(s)
Alice Challenge	2017	Web	Proprietary, free	Citizen science game	Ultracold atoms, experimental optimization
Hello Qiskit/Hello Quantum	2018	Web/iOS/ Android	Apache (web), proprietary, free (mobile)	Puzzle game	Quantum gates
Particle in a Box	2016	Web/MacOS /Windows	Proprietary, free	Single player platformer game	Superposition, energy levels
Psi and Delta	2018	Web/MacOS /Windows	Proprietary, free	Multiplayer platformer game	Superposition, energy levels, color-energy relationship
Quantum Game with Photons	2014	Web	MIT	Puzzle game	Photons
Quantum Odyssey	2020	Windows	Proprietary, paid	Puzzle game	Quantum circuits
Quantum Moves 2	2018	Web	Proprietary, free	Citizen science game	Ultracold atoms, optimal control, wavefunctions, and transport
Virtual Lab by Quantum Flytrap	2019	Web	Proprietary, free	Simulator/ puzzle game	Photons, quantum information, measurement

Finally, these different approaches introduced above can be supported by a criteria-based assessment, utilized by the quantum games hackathon juries organized by the Quantum AI Foundation to assess the submissions. These criteria are listed as correctness, playability, originality, and completeness for that particular hackathon (further information on the hackathon is provided in the Sec. 4.8.1):

- Correctness: Are the assumptions and usage of quantum mechanics and quantum computing appropriate?
- Playability: Is the game entertaining? Does it have educational potential? Is the user interface inviting?
- Originality: How creative and innovative is the idea?
- Quality and completeness: Is the game polished and ready to play? Are the mechanics well introduced?

To sum up, we are in the early stages of quantum games being accepted as a concept of their own, instead of just games designed to teach quantum physics. Therefore, development of evaluation tools and practices should also be considered to be an important research direction.

4.Experiences from the Field of Quantum Games and Interactive Tools Development

Computer-based games have evolved from a niche pleasure for a select few to a worldwide phenomenon that is now a part of the everyday lives of millions of people. Games have surpassed movies and television shows as a cultural, sociological, and economic force to be reckoned with. Games represent a new, robust economic sector that has amassed significant money, technological know-how, and skill for many nations. Games User Research[125] has become an essential aspect of game production, and many of the industry's most notable companies now adopt this methodology. This translates to higher product quality, tremendous financial success, and a more positive work atmosphere, in which employees can see evidence that their efforts are making a difference.

Serious games,[126] an umbrella term encompassing games having additional aims beyond entertainment, are extensively employed in various fields, including healthcare, telerehabilitation, military, and education. Serious games have always focused on the physiological and spatial consequences of the games on the participants.[127] Serious games and game technologies have been utilized for simulation and training in various areas, and these technologies have been adapted to computer, virtual reality (VR), and mixed reality (MR) settings. Milgram et al.[128] offered a precise method for differentiating between various realities, and MR has been characterized as "mixed virtuality and augmented reality," as well as "any combination of real-world and virtual-world features." The application of gaming technology in VR and MR has enhanced spatial task research while also allowing for immersion, presence, and usability studies.

The use of games and serious games has been a recent and powerful tool for experimenting with new quantum algorithms, providing new communication protocols, and teaching quantum theory to the masses. Recent advancements in implementing and testing quantum games have been an ongoing effort. In the rest of this section, we provide a selection of such games described by their developers.

4.1 Hello Quantum/Hello Qiskit

The IBM Quantum Composer was released in 2016 and provides a simple and graphical way to write quantum circuits and run them on prototype quantum computers. This service was (and is) available for free to the general public, allowing them unprecedented access to quantum computer hardware.[129] However, without the knowledge of what quantum circuits are or how quantum gates work, there was still a significant barrier to entry.

The Hello Quantum project, a collaboration between IBM Research and the University of Basel, was intended to alleviate this issue. The idea was to visualize quantum states and the effects of gates, so people could gain an intuitive understanding of simple quantum circuits.

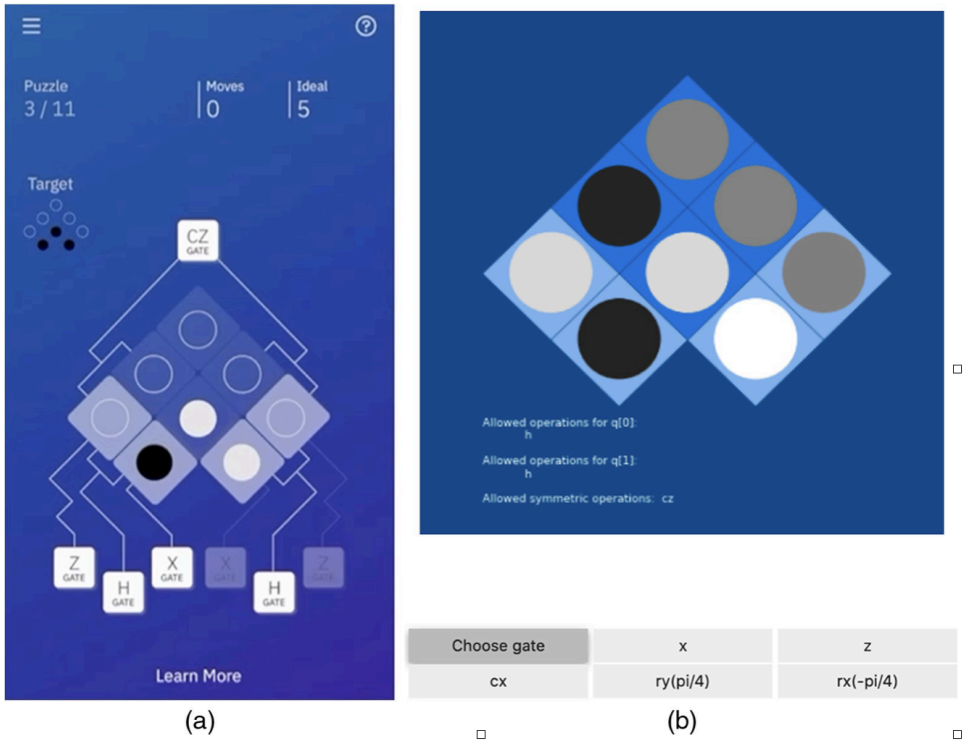


Fig. 4 (a) Screenshot of the Hello Quantum app and (b) a Jupyter widget-based puzzle from the Hello Qiskit section of the Qiskit textbook.

This interactive and visual method for learning was presented as a puzzle game, with the player being challenged to find the circuit that would take an input state to a desired output state.

The resulting products were released in four stages:

- A simple ASCII prototype, used in lectures at the University of Basel in 2017;
- The app Hello Quantum, released on iOS and Android in 2018[130] (Fig. 4);
- The section Hello Qiskit, released in 2019 as part of the interactive Qiskit textbook[131];
- The section "Visualizing Entanglement," released in 2021 as part of the interactive Qiskit introduction course.

In each case, the learning material was presented by providing interactive puzzles, intended to build intuition and provide context, as well as text providing an explanation of how aspects of the game relate to quantum computing.

For "Hello Quantum," the puzzles and text were delivered entirely separately. The idea was that the player could play through the puzzles as a short and informal game. Then, once they had mastered the game mechanic, interested players could go on to read about how their new in-game skills translate to quantum computation. This text was not limited to the app itself, but instead represented the inaugural posts of the Qiskit blog. These posts were entitled "Visualizing bits and qubits,"[132] which explained the visualization used in the app, and "Getting started with the IBM Q Experience,"[133] which explained how to transfer the learned skills into what is now called the IBM Quantum Composer.

It was expected that the readers would be led to the former blog post by the app and to the latter by a link in the former. However, view statistics show that only around 1% of views for the former can be traced to following the in-app link. Instead, the majority (around 58%) came from search engines. For the latter post, 81% of views come from sources external to the blog, such as 40% through email, instant message (IM), and direct and around 27% from search engines.

Given these results, we can conclude that the blog posts were a more successful learning resource than the app. This is because every app user who went on to fully understand the game will have followed the link to the app, but these app users are only a small percentage of the total readership.

For the "Hello Qiskit" section of the Qiskit textbook, the puzzles were implemented within an interactive Jupyter notebook. This was located in a chapter specifically for interactive demos. An analysis of views for the textbook was conducted for the period March to November, 2020.[60] It was found that the view share of this section is very comparable to those of the first two chapters. In fact, the average number of views for sections in chapters 1 and 2 during the period is very similar to the number of views for the "Hello Qiskit" section. During this time, 71% of views for the chapter come from within the textbook. These statistics suggest that it serves an integrated role as part of the introductory materials within the textbook. This motivated the more prominent usage of the visualization in the "Visualizing Entanglement" section of the new interactive Qiskit introduction course.

These results demonstrate an additional benefit to the design of quantum games and interactive tools. By finding visual and interactive representations of the mathematics behind quantum computing, we make it easier to describe. This allows us to create more engaging and understandable explanations in text. It is therefore worth considering making fully blog-based companions to any educational quantum game or interactive tool.

It is worth noting briefly that a similar insight was gained from the game Battleships with partial NOT gates. This was one of the first games to use a quantum computer and was designed primarily so that the source code could be explained in a blog post.[134] There is therefore little evidence of it being played, but the blog post remains the most viewed on the Qiskit blog by some margin.

4.2 Particle in a Box/Psi and Delta

"Particle in a Box" and "Psi and Delta" are digital games designed to support high school and undergraduate students in learning introductory quantum physics. The games were designed and developed as part of an interdisciplinary team of electrical engineers, media scholars, and HCI researchers comprised of undergraduate and graduate students as well as faculty at Georgia Tech. "Particle in a Box" aims to support learning quantum physics by allowing students to virtually explore, compare, and experiment with worlds that follow the laws of classical and quantum physics.[61–63,135] Building upon Particle in a Box, Psi and Delta aims to teach quantum physics through collaborative inquiry by requiring two players to cooperate, develop, and employ concepts of quantum mechanics together to resolve challenges involving quantum physics.[136] Both games can be downloaded and played at Ref. 137. Both games integrate quantum physics into the game mechanics using a concept map of the infinite square well. For example, to reify the concept of light color affecting energy levels, Particle in a Box requires students to find and collect light bulbs of the appropriate color and bring them to a lamp to shine light onto an electron. Similarly, to promote engagement with the relationship between "area under the curve" (the curve referring to the probability distribution of the electron) and the probability of the electron, Psi and Delta uses platforms with different widths and measurement counters that count how many times an electron is measured under each platform to express probability. The concept map of the square well problem used by both games is provided in Fig. 5.

4.2.1 Particle in a Box

Particle in a Box is a 2-D single-player platformer game built in Unity in which the player plays the game through a virtual avatar who travels through a 2-D rendition of the classical and quantum worlds. The classical world, set in a lab-like environment, (Fig. 6) involves challenges based on Newtonian physics such as jumping over a ball and increasing its total energy. After playing the classical world, players shrink down to the quantum world (Fig. 7) which is based on the infinite square well problem. It involves an electron that is trapped in a 1-D quantum wire and exhibits quantum behavior such as superposition and energy quantization. The challenges here are based on understanding introductory quantum physics. Experiencing both worlds affords students the opportunity to compare their similarities and differences—an approach that has shown to be effective in learning quantum physics.

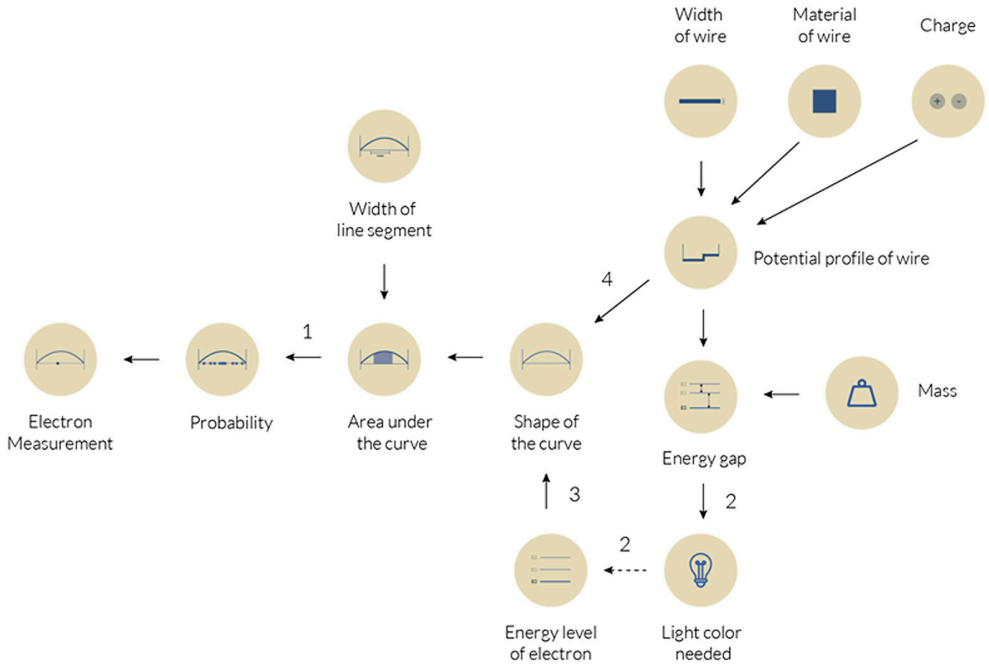


Fig. 5 The Concept Map of the square well problem.

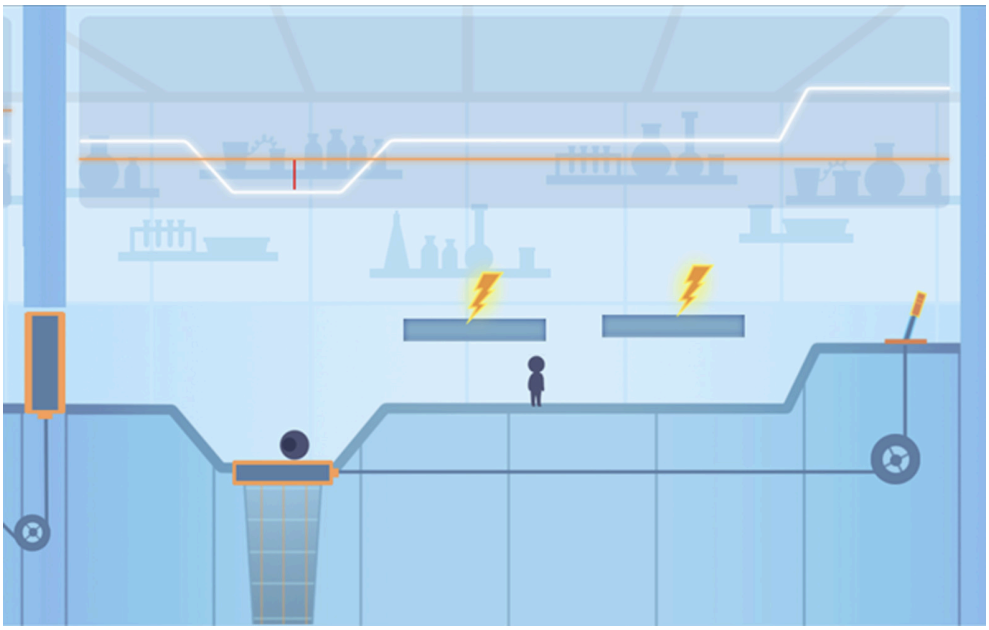


Fig. 6 The classical world in Particle in a Box. The player must reach the energy bolts, carry them, and place them in the path of the moving ball.

Both worlds have similar objectives: to raise a particle's energy. In the classical world (Fig. 6), the objective is to raise the energy of a rolling ball so that it pushes a lever located higher up, which opens the door to the next level. In the quantum world (Fig. 7), the objective is to increase an electron's energy up 3 levels by gathering light bulbs of the correct color and shining light on the electron's quantum wire. Having similar objectives enables direct

comparison between concepts such as position and energy, which manifest differently in classical and quantum physics.



Fig. 7 The quantum world in Particle in a Box. The player must carry the colored bulbs to the lamp (left) that will shine light and increase the electron's energy level (top). The blue dot is the electron, and the bright line it is on is the wire. The curved white line illustrates the wavefunction of the electron.

Further, in both worlds, if the player hits the particle, they faint and must restart. In the classical world, this means coming into contact with the ball. In the quantum world, this means coming into contact with the measurement of an electron particle. The electron by default is in a state of superposition. However, it is also measured regularly and "appears" each time as a particle. The position where this electron particle appears is random but follows a probability distribution (curved white line in Fig. 6). Through repeated measurements, the game simulates an "experience" of probability as the player learns to identify the locations where the electron is likely to be measured and therefore where they are more likely to be hit. Because players faint if they are hit by the particle in either world, they must learn to carefully analyze the behavior of those particles in both worlds, thereby promoting further comparison.

Particle in a Box was evaluated with undergraduate electrical engineering students at Georgia Tech and showed an improvement in students' conceptual understanding of probability.[61] Students further reported an increase in comfort level with the key concepts taught in the game. The game was awarded the Student's Choice Award at the Serious Games Showcase and Challenge in 2015.

4.2.2 Psi and Delta

Psi and Delta builds on our findings of Particle in a Box by students adopting the role of two robots, with the aim of defeating opposing robots in a world governed by the laws of quantum mechanics. Students accomplish this task using concepts of quantum mechanics to lure and "shock" the opposing bot. If a student's bot touches the opposing bot or gets "shocked," it loses part of its health. If any player's bot loses all of their health, the level restarts.

The game is divided into two parts. In part one, the students develop models of the concepts of superposition and probability (Fig. 8). As discussed earlier, when an electron is confined in a small area, it will enter a superposition state, i.e., it will exist in multiple positions simultaneously. To break this superposition, one needs to take a "measurement." In the game, the electron is confined to a small blue quantum wire. In contrast to the automatic measurements, in Particle



Fig. 8 Taking a measurement in Psi and Delta. One player (left) takes the measurement by pulling a lever, while the other (middle) lures the enemy bot to a higher probability area. Here, the enemy bot is shocked by the measured electron as it stands on a platform under which the electron was measured.

in a Box, it is the players who take measurements by pulling a lever. Each time a player pulls the lever, a measurement is taken, which collapses the electron from its superpositions state to an unpredictable position on the wire for a brief moment. Any robot (player or enemy) standing on a platform directly above the collapsed electron will get "shocked" and lose some health (see Fig. 8). The position where the electron collapses is probabilistic, i.e., some positions are more likely than others. The relative probability of these positions is illustrated by the electron's prob- ability distribution, the orange curve in Fig. 8. The longer the platform is and the higher the curve above it is, the more likely the electron will be measured under it. After each measurement, the electron returns to superposition.

In part two, students develop models of energy levels (Fig. 9). Here, the opposing bot has a shield that protects it from getting shocked. To break the shield, the electron needs more energy. Electrons can only have a discrete amount of energy such as 1 eV (electron-volt) or 3 eV in the case shown in Fig. 9, but nothing in between. Energy can be supplied to an electron in the form of light, which consists of discrete energy packets (photons) with energy that depends on their color. To excite an electron from a lower energy (say 1 eV) to a higher energy (3 eV), one must shine photons with the exact energy as the gap (2 eV). In the game, students can shine light using a lamp and change its color using a spectrum.

This collaborative inquiry approach encourages students to share their ideas and work together to understand basic quantum physics concepts.[136] Qualitative evaluations of Psi and Delta with undergraduate physics and astronomy students showed that it was effective at engaging them with the basic concepts of quantum physics and had potential to be integrated more formally into traditional lectures.[18] The game was also presented at the Smithsonian Creativity and Innovation Festival held at the National Museum of American History in Washington DC.

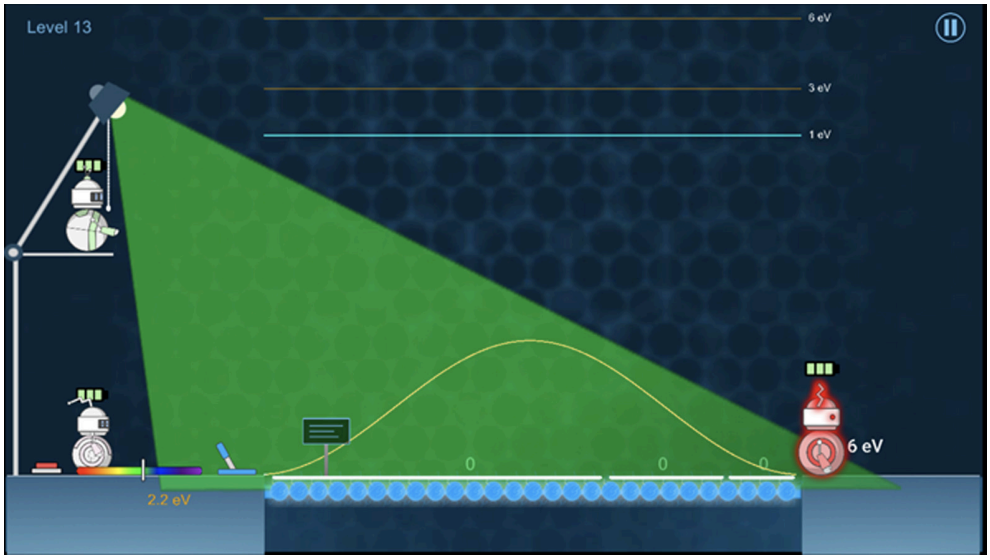


Fig. 9 Shining light to increase the electron's energy level in Psi and Delta. The horizontal lines on top indicate the electron's energy levels. The spectrum (bottom-left) lets players change the color of the light shined.

4.3 QPlayLearn

QPLayLearn[138] is an online platform conceived to explicitly address, within a global strategic vision, the challenges and opportunities of widespread quantum literacy. QPlayLearn was born from a group of scientists passionate about quantum science and firmly believing that everyone can learn about quantum physics and its applications. QPlayLearn's mission is to provide multilevel education on quantum science and technologies to anyone, regardless of age and background. To this aim, interactive tools enhance the learning process effectiveness, fun, and accessibility, while remaining grounded with scientific rigor. As a strategy for cultural

change in a wide range of social strata, QPlayLearn offers diversified content for different target groups, from primary school to university physics students to quantum science enthusiasts. It is also addressed to companies interested in the emergent quantum industry, journalists, and policy makers needing to grasp what quantum technologies are about.

Inspired by the theory of multiple intelligences,[139] QPlayLearn's holistic perspective stems from the recognition that different types of intelligence dominate the learning process of each person. Therefore, the platform is conceived to accompany users via different paths aimed at (1) building intuition and engagement through games and videos; (2) understanding physical concepts through accessible and scientifically accurate descriptions, graphics, animations, and experiments; and (3) acquiring formal understanding through mathematics. Such a three-step method is used in Quest, the QPlayLearn quantum dictionary, in which each entry is composed of various sections exploiting different kinds of learning-approaches and resources. For each concept in the dictionary, each user can begin from the approach that feels easier to them and then possibly explore the others. Eventually, it is the combination of the different pathways that shifts and expands the understanding of quantum physics and technologies.

In this context, games are one of the tools, embodied in the section Play, to stimulate the interactive participation of the users to grasp the counterintuitive features of quantum physics. In addition to games, short animations (Quantum Pills) explain concepts at different depths of understanding, which is useful for experts and nonexperts. In the Discover section, specialists explain concepts with short videos, using metaphors, experiments, or deductive examples. The Learn section enters the formal core of quantum theory, devoted to a more expert audience. In the Apply section, concepts can be practiced by running code samples on real-world quantum devices. Finally, there is also a space dedicated to art and science projects, as art can help bring people closer to science and quantum technology in a way that goes beyond academic learning or scientific popularization.

Because of the foundational concept, QPlayLearn is aimed at wide and diverse (free) use, to tailor education processes on quantum science on the many aptitudes of different users, operate a diffuse and massive cultural change, and build up literacy and awareness. Because of this flexibility, QPlayLearn can be incorporated by educators in a widespread context. The effectiveness of the QPlayLearn approach needs to be assessed by means of physics education research tools in on-purpose designed experiments. Meanwhile, a number of developments are underway; these include completing the quest environments, adding a multiple language version, and extending the class of beneficiaries to 0 to 99 years old users, together with pedagogy experts. In fact, the latter represents an authentic priority and an unprecedented challenge.[18]

4.4 Virtual Lab by Quantum Flytrap

Quantum Flytrap is a company founded in 2019 that is focused on bringing quantum technologies closer to users by developing user-friendly graphical interfaces. In addition to on-going commercial projects involving developing a no-code Integrated Development

Environment (IDE) for quantum hardware, Quantum Flytrap provides educational tools to demonstrate capabilities of interfaces and real-time simulations.

Virtual Lab by Quantum Flytrap (2019)[140] is a real-time online simulation of an optical table, supporting up to three entangled photons. The Lab uses a drag-and-drop interface for positioning optical elements, such as photon sources, mirrors, polarizing and nonpolarizing beam splitters, and Faraday rotators. The inspiration comes from ease of use and capabilities of construction systems, such as LEGO Bricks, the Goldberg machine video game The Incredible Machine,[141] and grid-based games such as Chromatron and Minecraft. Most elements have configurable parameters such as phase shift (for reflections, delays, and wave plates), polarization rotation (for Faraday rotators and sugar solutions), and absorption rate. The Lab supports both destructive measurements and nondemolition POVM measurements.

Virtual Lab is a successor to Quantum Game with Photons (2016),[142] an open-source puzzle game with 34 levels and a sandbox. Quantum Game with Photons simulates a single photon and its polarization. Although most setups could be understood within the framework of classical wave optics, the binary character of photon detection shows a few quantum phenomena. For example, the game demonstrates the Elitzur–Vaidman bomb tester—an experiment in which the quantum measurement plays a crucial role.

The original Quantum Game with Photons had over 100k gameplays and was cited in seven peer-reviewed publications by unrelated researchers.[18,143–148] It was selected as the top pick in gamifying quantum theory in *The Quantum Times*.[149] Based on in-person and email feedback, we learned that it was possible to solve a large fraction of levels without prior exposure to quantum physics, e.g., for high school and undergraduate students. At the same time, a few levels provided a challenge to PhD students and established quantum optics professors.

Virtual Lab is focused on reinventing the interface, design, and numerical performance. Our simulation supports multiparticle quantum physics. Unlike most other simulations, it goes beyond qubits. Virtual Lab simulates pure quantum states with photon polarization, four cardinal directions, and a discrete position of a photon on a grid. Consequently, for a typical grid size, a single photon requires around 1000-dimensional vector space, so a three-photon simulation requires a billion dimensions. Therefore, Quantum Flytrap needed to develop a custom high- performance sparse array simulation in the low-level programming language Rust—as none of the off-the-shelf solutions were suitable.

Virtual Lab offers a set of example experimental setups demonstrating key experiments in quantum measurement, quantum cryptography, quantum communication, and quantum computing. Example setups involve single photon experiments, such as nonorthogonal state discrimination, the Elizur–Vaidman bomb tester, the BB84 quantum key distribution protocol, and the concept of nondemolition measurement affecting interference. The two-particle setups include the Ekert quantum key distribution protocol, the Deutsch–Jozsa algorithm, and the CHSH Bell inequality violation. With three particles, we can demonstrate quantum teleportation and Greenberger–Horne–Zeilinger correlation (Fig. 10).

The measurement results can be subject to logical operations (such as AND or XOR), used to alter other elements (e.g., to perform quantum teleportation), treated as a goal (for puzzles and course assignments), correlated (for Bell inequality violation), or saved as a CSV table for arbitrary processing.

Moreover, a laser mode allows us to explore classical wave phenomena, such as the three-polarizer paradox (generalizing to the quantum Zeno effect), interferometers (Mach–Zehnder, Michelson–Morley, Sagnac), optical activity, and magneto optic effect (with applications such as an optical diode).

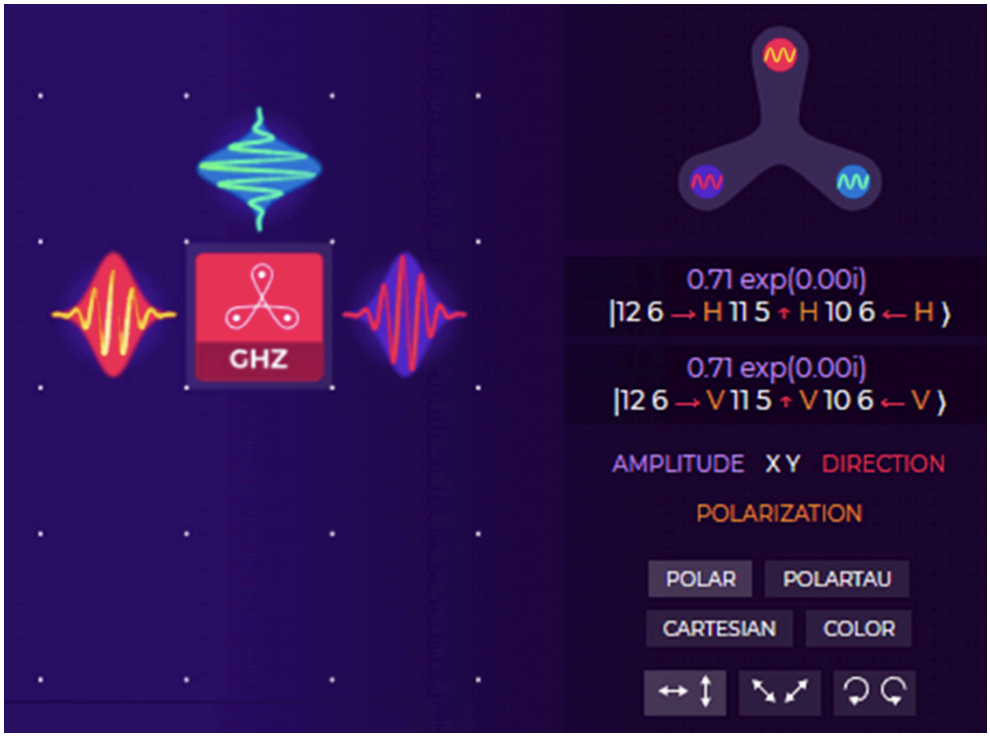


Fig. 10 A three-particle Greenberger–Horne–Zeilinger entangled state, visualized simultaneously as (A) waves on the board, (B) entanglement between particles, and (C) the quantum state, in bra-ket form.

Virtual Lab provides multiple ways to investigate an experiment, its outcomes, and the current quantum state. The multiverse tree feature allows users to explore the whole experiment, including all possible measurement scenarios. In the Copenhagen interpretation, all branches are related to probabilistic outcomes. Within the Everettian many-world interpretation, each branch is a coexisting part of the quantum state, representing worlds that are unlikely to interfere with each other.

In each time step, it is possible to explore the exact state (ket) with a preferred choice of the basis and coordinates of complex numbers. Furthermore, we visualize entanglement of every particle with the system.

Virtual Lab has been used for quantum information courses at Stanford University and the University of Oxford, as well as by Qubit for Qubit's Introduction to Quantum Computing online course. Virtual Lab features over 450 custom, user-created setups. It has around 70 users on a regular working day and peaks at over 700 during events.

Quantum Flytrap released Quantum Tensors[150] is an open-source JavaScript library for in-browser quantum information processing. It goes beyond qubits and supports physical multiparticle physical systems (polarization of light and spin), as well as qudits. It allows for the creation of states, changing bases, performing unitary operations, measurements (destructive and nondemolition POVMs), and entanglement entropy. It has sparse linear algebra operations (including with tensor products) and support for quantum circuits.

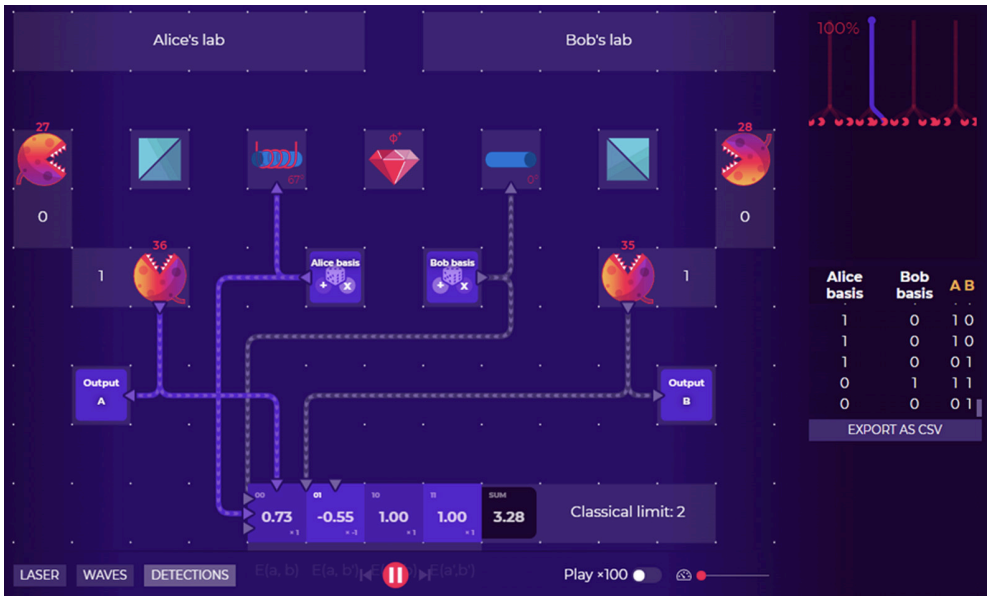


Fig. 11 An experimental setup for the CHSH Bell Inequality violation. Note that the experiment depends on two random variables (Alice's and Bob's basis), provides a table of all measurements (downloadable as a CSV file), and presents all correlation in real time.

Virtual Lab allows for exploration of quantum states at each single time step (see Fig. 11) and matrices for unitary operation and projections (see Fig. 12). Quantum Flytrap open-sourced BraKetVue (or φ ψ .vue)[151] is a visualization of quantum states and operations in the popular web-development framework Vue.js. It allows for the creation of interactive quantum explorable explanations (e.g., in a blog post with an introduction to quantum gates[114]) and can be used in other web-based environments, such as presentations with Reveal.js (created in RISE in Jupyter Notebook or with R Markdown). Matrix visualizations allow us to show the magnitude and phase of transition in a visual way, dynamically change the basis, and explore the tensor structure (e.g., change the order of particles).

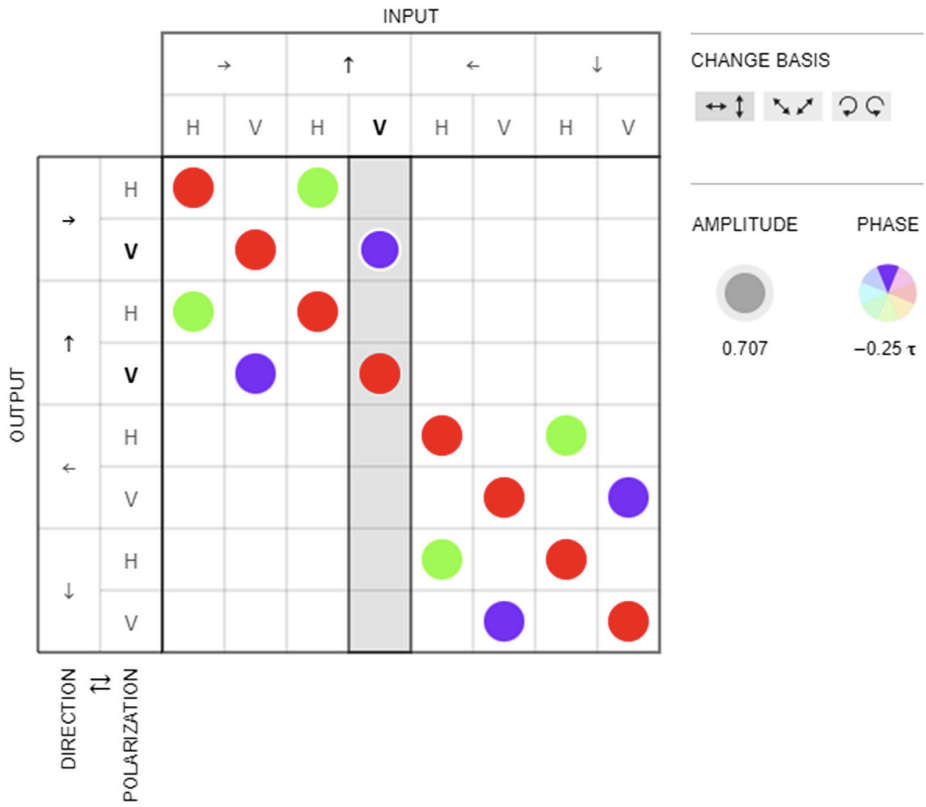


Fig. 12 A matrix visualization for a beamsplitter with BraKetVue. The matrix values are presented with a circle size (radius for the amplitude, area for the probability) and color (hue for the phase). Index labels incorporate the tensor structure.

4.5 Quantum Odyssey

Quantum Odyssey is a privately funded, large software project, still in development by Quarks Interactive,[152] but the alpha version is already available for the public. Currently, the software comes with over 20 h of fully narrated, from quantum optics phenomena to coding quantum algorithms. The software also contains a vast encyclopedia that verbosely explains key quantum mechanics concepts. People working on the software have various backgrounds (researchers in education, quantum physicists, artists, and game developers).

Behind Quantum Odyssey is the concept of quantum literacy, as coined by Nita et al.[19] The aim of Quantum Odyssey is to make quantum physics and computing knowledge accessible to all audiences, regardless of their background, by making learning about and working with quantum algorithms exciting and fun. Quantum Odyssey is a fully visual and software-assisted method for learning how to create new and optimize quantum algorithms for quantum computers. Equivalent to everything that can be achieved using the gate model framework, users can design quantum algorithms for any purpose (ranging from designing physical interactions in optics to more advanced quantum computing algorithms) without requiring any background knowledge in STEM. Quantum Odyssey shows in real time the dynamics of the quantum state vector, including its evolution as the user adds quantum gates to build quantum algorithms (Fig. 13).

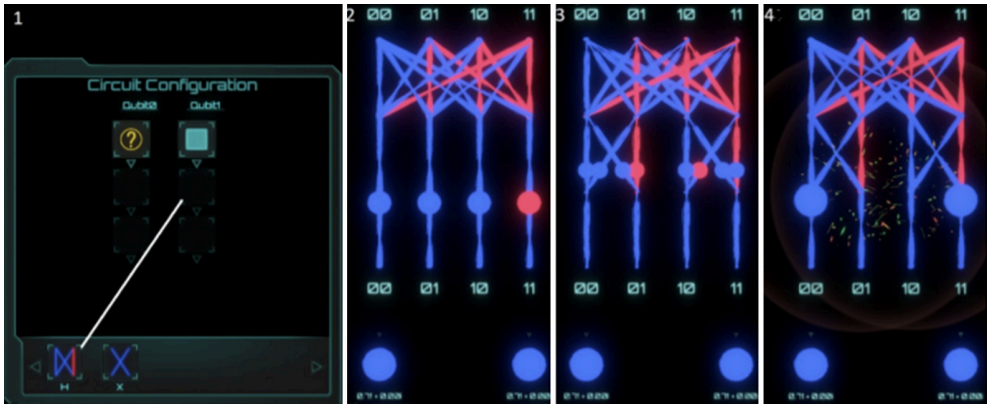


Fig. 13 Images 2, 3, and 4 are snapshots of the evolution of a quantum state vector in visual form for two particles that start in the ground state 00 and reach the Bell state 00 and 11. The balls at the bottom show the desired output solution, and the user is required to place a Hadamard gate to achieve it as shown in 1.

The software was tested in schools and found to be suitable for teaching quantum physics and computing from the age of 12 and above. The results of the research study[118] show that the Quantum Odyssey visual methods are efficient in portraying counter-intuitive quantum computational logic in a visual and interactive form. This enabled untrained participants to quickly grasp difficult concepts in an intuitive way and solve problems that are traditionally given today in master's level courses in a mathematical form. The results also show an increased interest in quantum physics after play, with a higher openness and curiosity to learn the mathematics behind computing on quantum systems. Participants developed a visual, rather than mathematical, intuition that enabled them to understand and correctly answer entry level technical quantum information questions. Another interesting find is that the design of the visuals of the software makes it equally appealing to both female and male participants, that is, both genders were found to be equally able to solve complex mathematical problems if they were given in a visual puzzle form within Quantum Odyssey.

In future releases, the following new features will be introduced:

- The ability to import/ export visual puzzles to IBM Qiskit and run algorithms right on an IBM QCPU. Everything designed with Quantum Odyssey is fully compatible with Qiskit.
- Multiplayer, collaborative efforts in optimizing and discovering new quantum algorithms.
- Community puzzle publishing and ranking system for puzzle creators and puzzle solvers.

4.6 ScienceAtHome

ScienceAtHome[153] was founded in 2011 at Aarhus University with the goal of developing gamified tools to enable citizen scientists to participate in cutting-edge quantum research.

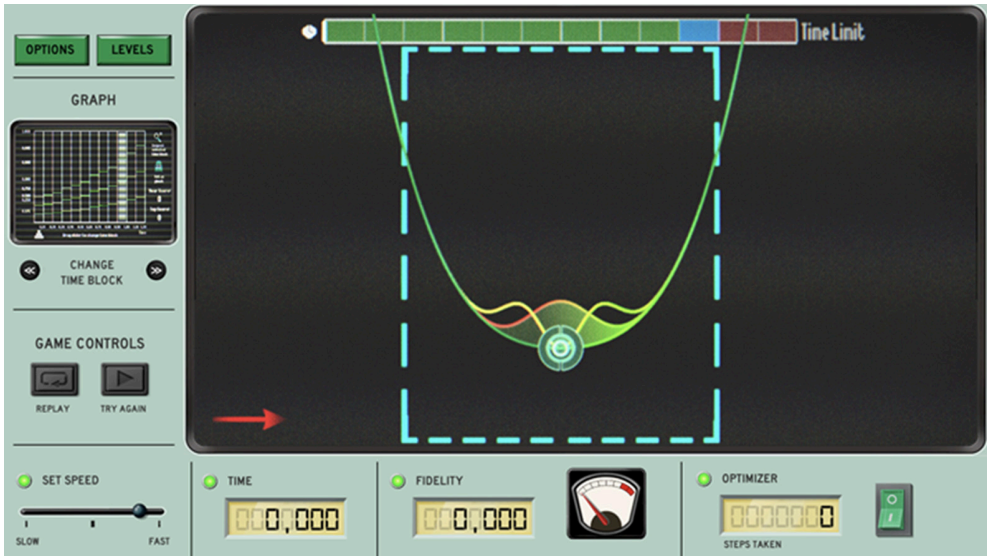


Fig. 14 The Quantum Moves 2 interface, showing the *Shake Up* level. The goal is to move the potential (green line) left and right within the cyan dashed box to excite the quantum fluid (green shaded curve with red-yellow outline) from its initial, ground state (as shown) to the final, first excited state (yellow outline). This must be done within a certain amount of time, and the goal is to achieve the highest overlap (fidelity) between the final state and the yellow-outlined state. For more information, see Ref. 117.

Today, ScienceAtHome boasts a suite of games and tools for education and citizen science in a variety of academic fields. ScienceAtHome's flagship game is Quantum Moves 2[154] (Fig. 14), a game in which citizen scientists can play through a variety of scenarios, including three scientific problems relevant to cutting-edge research in quantum technologies. To date, at least 250,000 players have played Quantum Moves 2. Research has shown that player-generated solutions could have some advantages over random seeding when applied to optimization of the scientific problems, even when the solution landscapes of these problems are complex.[117] In particular, players explore the solution landscape more efficiently and can capture solution strategies that algorithms may miss. This is not to say that players are better than algorithms, but rather that the insights of citizen scientists can be useful when deciding how to solve a given quantum problem.

In 2017, researchers at ScienceAtHome opened up their quantum laboratory to the general public in the Alice Challenge.[155] The goal of the Alice Challenge was for users to optimize the number of rubidium-87 atoms in a Bose-Einstein condensate, or BEC,[156,157] a cloud of extremely cold atoms that can then be used for a variety of quantum technology experiments. We found that citizens operating the experiment remotely[158] were able to create larger BECs than the local experimental experts,[159] a difference that we attribute largely to interfacing and gameplay (Fig. 15), that is, we built a simple and intuitive interface that allowed citizens to collaborate (in that any player could copy a previous solution and modify it) to solve the problem-at-hand; such intuitive interfacing is key to success when considering citizen science projects, quantum or otherwise.

ScienceAtHome has also developed a number of educational tools, including the Quantum Composer,[86] which is built on the QEngine C++ library;[160] both tools are freely available for download and use. The QEngine is a research tool for the simulation and control of 1-D quantum mechanics,[161] and the Quantum Composer wraps the functionality of the QEngine into a flowbased tool for quantum visualization. Thus, the Quantum Composer (Fig. 16) is aimed at introducing students to quantum mechanics and quantum research via a modular interface that can be used to simulate a wide range of problems in introductory and advanced quantum mechanics, including those that are not analytically tractable. [87,88]

ScienceAtHome researchers and educators have used these tools in a number of educational and outreach settings, including the aforementioned week-long Alice Challenge in 2017 in which 600 citizen scientists around the world took part. Quantum Moves 2 featured heavily in the 2018 ReGAME cup,[162] with more than 2000 students from 200 high school classes around Denmark playing a set of citizen science games as they worked through educational content that scaffolded the games, and the planned Project FiF[163] (Forskningsspil i Folkeskolen, or research games in high schools) will expand this to 150 schools around Denmark. Quantum Composer has also been widely used as a part of ScienceAtHome outreach efforts in Denmark and around Europe, including a 3-year-long outreach training effort coordinated as a part of the quantum sensing and control (QuSCo[164]) Marie Skłodowska-Curie interactive training network.[165] The outreach training program was aimed at teaching PhD students to communicate their research via a variety of methods, including videos, blog posts, and the development of inquiry-based learning sessions.



Fig. 15 The interface for the Alice Challenge, showing (a) the spline curves that the users could manipulate to control the time-dependent laser powers and magnetic field coil currents that controlled the final BEC atom number, (b) a top score list, (c) a list of the latest submissions and their scores, and (d) a control toolbar, including the estimated wait time. Players could take any other player's solution [as shown in (b) and (c)] and modify it. Figure reproduced from Ref. 158.

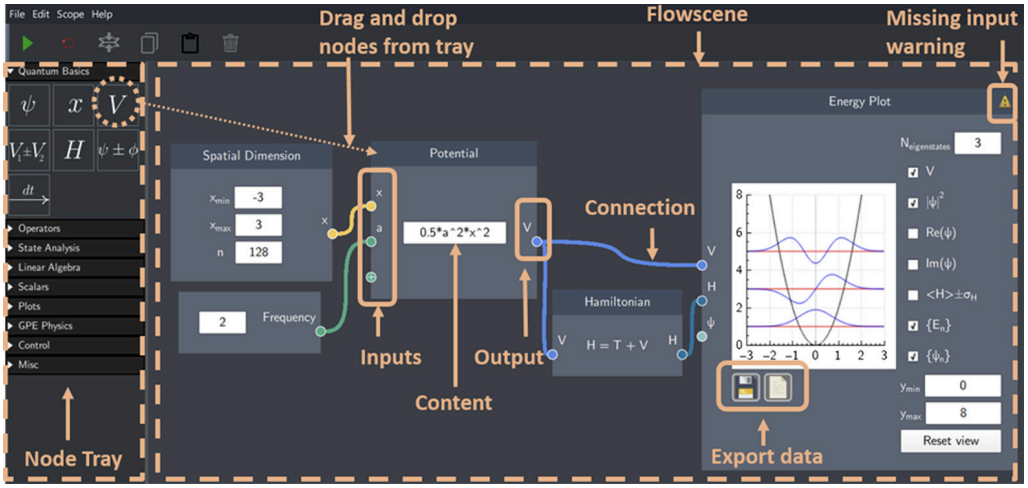


Fig. 16 The Quantum Composer interface. Users can drag-and-drop nodes (representing space, the potential, a plot, etc.) from the left-hand tray into the simulation space (called a flowscene). Connections are then made between the nodes to direct information from one node to another. This figure shows how one can set up a simulation that shows the first three eigenenergies and eigenstates of the quantum harmonic oscillator. Figure reproduced from Ref. 87.

4.7 Virtual Quantum Optics Laboratory

The Virtual Quantum Optics Laboratory (VQOL) is a graphical web-based software tool for designing and simulating quantum optics experiments[166,167] developed by the Applied Research Laboratories at the University of Texas at Austin. The VQOL was developed initially as an educational tool for introducing high school and early college students to quantum information science, but it has also proven to be useful as a research tool for analyzing real-world experiments.[168] The graphical interface presents a top down view of a notional optics table with a menu of components that can be placed and configured as desired. To aid visualization, six base colors are used to represent polarization and interpolate these across the Poincaré sphere (see Fig. 17). A variety of components are available; these include passive linear optics (waveplates, polarizers, beam splitters, etc.), light sources (LEDs, lasers, and Gaussian entangled states), and measuring devices (power meters and detectors).

In an educational setting, VQOL may be used to introduce optics concepts (either classical or quantum) or to explore quantum phenomena and applications. Over the past 2 years, we have used VQOL as part of a full-year high school course on quantum computing[169] as well as part of a two-semester introduction to quantum computing for university freshmen and sophomores. A typical introduction to qubits begins with the concept of polarization, which can easily be understood in terms of transverse waves on a string. We then introduce projective measurements through an initial investigation of Malus's law using a laser, polarizer, and power meter. We transition to the Born rule by introducing a neutral density filter, which attenuates the laser light to the single-photon regime, and replacing the power meter with a detector for photon counting. Students perform guided experiments and explore the phenomena before drawing inferences to uncover the physical laws behind them. Upon this

foundation of physical intuition, a more concise abstract mathematical description may then be introduced. One important aspect of these experiments is that students are challenged to consider appropriate data analysis methods for conceptually connecting “counts” with probabilities. Because, from an experimental point of view, there is not a well-defined number of “trials,” this exercise raises interesting interpretive questions. Students must consider how to normalize their data and account for dark counts, just as they would need to do in a physical optics lab.

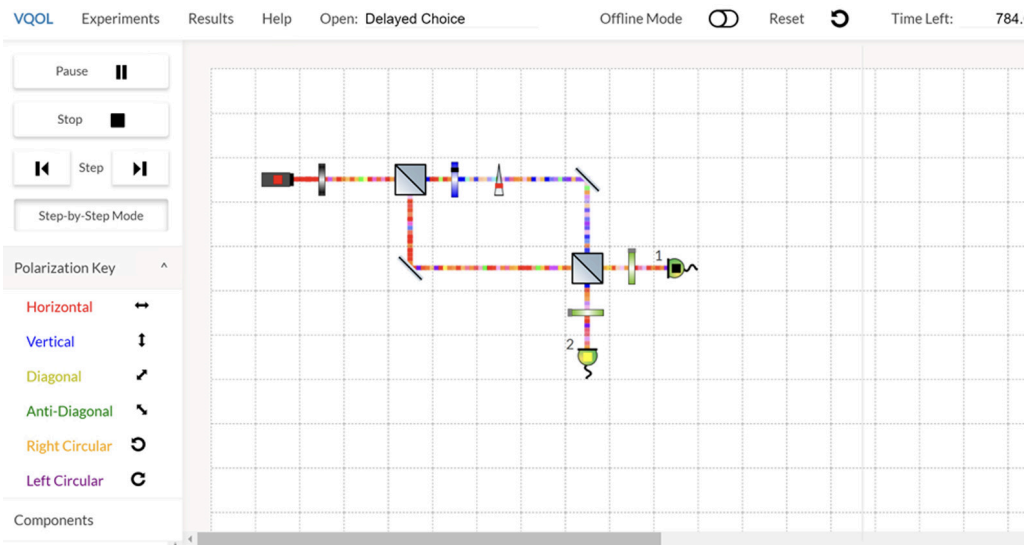


Fig. 17 Screen shot of the VQOL interface showing a delayed-choice experiment. A laser (left) produces horizontally polarized light (red) that is attenuated by a neutral density filter before entering a Mach–Zehnder interferometer. The random polarizations (multiple colors) are due to vacuum noise. The upper arm has a half-wave plate (blue disk) that can provide which-way information by changing the polarization to vertical (blue). The two detectors have polarizers (green disks) to detect horizontal light.

Beyond introducing elementary concepts, we have also used VQOL for deeper explorations into quantum physics. Over the past 2 years, we have offered a virtual experimental quantum optics program to our university students. The program aims to connect theory to experiment by exploring quantum information science in an experimental optics setting. Students work in groups of two to four individuals and are tasked with exploring about 10 different experiments over a 9-week period. Students select which experiments to investigate and are given only general guidance on the goals and phenomena to be explored. At the end of each week, the groups get together to present and discuss their findings. Possible experiments include quantum state tomography, an optical implementation of Deutsch’s algorithm, delayed choice and quantum eraser experiments, quantum teleportation, entanglement swapping, and violations of Bell’s inequality.[166] We have found through post-program surveys that students generally respond well to the open-ended nature of the experiments and feel that it gives them a more authentic research experience than traditional, more structured undergraduate laboratories.

4.8 Activities in Creating Quantum Games

The first recorded hackathon was organized by developers of the OpenBSD[170] software in June 1999, and the term was coined by its organizers. It is commonly used to refer to "a usually competitive event in which people work in groups on software or hardware projects, with the goal of creating a functioning product by the end of the event."[171] The first (or the zeroth depend- ing on the perspective) game jam was organized by The Indie Game Jam community in March 2002.[172] It usually refers to a more relaxed and noncompetitive event compared to a hackathon, similar to a jam session of a musical band. The created games can have educational or research value.[173] Moreover, a game jam can foster creativity, learning, and collaboration of the game developers to explore technologies and develop skillsets.[174] Since their emergence, both terms have been adopted by software communities and beyond, and the number of hackathons and jams have grown to hundreds per year.[175] Therefore, their adoption by the community of quantum game developers was not a surprise. Some further readings on game jams can be found here.176–180

The first quantum game jam was organized in Finland in 2014 as a part of the Finnish Game Jam,[181] and the first quantum hackathon (not focused on games) was organized in April 2018 by Rigetti,[182] where two quantum games were also developed. Following these, several quantum game jams[183] and hackathons focused on game development were organized. Reference 183 describes the organization of five quantum game jams and rates for each the quantum game developed based on how enjoyable and informative on quantum concepts that it was.

In what follows, we provide a recent example of a quantum games hackathon organized in September 2021. This is followed by the description of a quantum computer games project-based course at the University of Texas at Austin, organized by the developers of the previously introduced Virtual Quantum Optics Laboratory tool. Both examples are described by their organizers in detail, to be used as templates by any interested readers.

4.8.1 Quantum Games Hackathon by Quantum AI Foundation

The Quantum Games Hackathon[184] was an online event organized in 2021 by the Quantum AI Foundation (QAIF)[185] in collaboration with members of QPoland,[186] a QCousins branch of QWorld.[187] The event was related to the Warsaw Quantum Computing Group meetups.[188] The main motivation of this hackathon was to popularize and foster innovation in quantum computing as well as to provide the participants with an opportunity to develop quantum programming skills. The hackathon started with two days of introductory talks and workshops (September 25 and 26, 2021) followed by a week for project development. The submission deadline, as well as the announcement of the winners, was the third of October 2021. In addition, QAIF and QPoland organized a separate workshop prior to the hackathon based on QWorld's Bronze[189] material to give participants more time to learn necessary skills.

The invitation to the event was shared on social media platforms: Facebook, LinkedIn groups, and Twitter. There were 128 registrants from 41 countries. The participants worked in teams composed of up to five people, formed during a match-making event. Participants were

advised to have team members with expertise in different domains, e.g., quantum programming, user experience design, business development, computer games development, etc. Communication within teams, with mentors, and with the organizers was held using the hackathon Discord server. In addition to the quantum computing workshop, participants had an opportunity to listen to lectures given by experienced researchers, developers, and entrepreneurs working in the quantum computing domain. The talks, given over 2 days at the beginning of the hackathon, included introductions to software and programming platforms (Qiskit and the JavaScript environment), existing games (e.g., Quantum Odyssey), and interface design and accessibility in games. All lectures were given using Zoom; most of them were recorded and are available on QAIF's YouTube channel.[190]

At the end of the event, seven solutions were submitted. According to the hackathon rules, the participants were requested to submit a link to a public GitHub repository containing the quantum game code and a short video presentation (up to 5 min). All submissions were assessed by a jury composed of six members according to the following criteria:

- **Correctness:** Are the assumptions and usage of quantum mechanics and quantum computing appropriate?
- **Playability:** Is the game entertaining? Does it have educational potential? Is the user interface inviting?
- **Originality:** How creative and innovative is the idea?
- **Quality and completeness:** Is the game polished and ready to play? Are the mechanics well introduced?

The three best projects were awarded prizes; there was also an additional prize funded by *Quantum Flytrap* for the best game developed using *JavaScript*. All other prizes were awarded by the other Strategic Partners of the hackathon: Snarto, Cogit, Quantumz.io, and KP Lab. The winning solutions were:

- **DaveTheHackerman_ZXgame,**[191] a game on diagrammatic ZX-calculus.[192]
- **QuanTetrum,**[193] a Tetris-inspired game that uses three important concepts of quantum physics: superposition, entanglement, and measurement.
- **QG_Crusher,**[194] a Candy Crusher-like game with quantum gates.
- **Quaze,**[195] a quantum maze in which each maze tile is a gate changing the state of a quantum particle.

4.8.2 Quantum computer games project-based course at the University of Texas at Austin

For the mid-semester project in the Quantum Computing stream of UT Austin's Freshman Research Initiative (FRI) seven groups of one to three students were tasked with programming their own games to run on quantum computers. In a short lesson introducing the concept of quantum games, we briefly covered motivations for designing games including showing off or testing state-of-the-art hardware, engaging participants for the purposes of education and

entertainment, and, importantly, as a creative exploration of new technologies. For the purposes of the project, we defined a game as something with a goal, rules, and feedback. The player uses the rules to attempt to accomplish the goal; feedback is received and, depending on the particular game, may be used to modify the player's strategy. To avoid overly contaminating the students' creativity, we added only that each game must contain four essential quantum effects: superposition, interference, entanglement, and measurement. All of these quantum features must be present for the player to manipulate and/or experience.

When designing quantum computer games, students must consider each of the four required quantum effects from a creative perspective rather than simply in an academic context. Using Qiskit, our class builds many of the popular quantum algorithms including Deutsch-Jozsa, Grover search, phase estimation, and factoring; though our teaching style tends to be exploratory, we eventually lay out the algorithms in easy-to-follow steps. The students must understand the steps to apply them in a computer program and analyze the results. In this game-making project, the students do not have concrete steps to follow. Instead, they must either fit quantum effects into a pre-existing game or build original rules around the desired quantum effect. This takes comprehension of quantum concepts as a prerequisite and pushes the student beyond simple understanding into experimentation and imagination.

Each group submitted their programmed game along with a written report highlighting the quantum aspects of their game, potential strategies, and any other interesting features. They also each gave a brief (5 to 7 min) presentation and gameplay demonstration. The game titles and short descriptions are included below.

- **Qhess:** Chess in which each piece can move in superposition. At each turn, all of the potential states of a piece must be considered when moving that piece. Measurement occurs when pieces interact by occupying the same square.
- **Quantum Mafia:** A quantum version of the party game, Mafia. Each villager chooses a decimal number as their phase. The mafia member uses quantum phase estimation to attempt to kill the villager. The mafia RSA encrypts their identity, and the detective uses Shor's algorithm to attempt to discover them. The doctor uses the Deutsch–Jozsa algorithm to attempt to save targeted villagers.
- **Quantum Boss Battle:** You must battle a boss monster whose health is represented by a random entangled circuit. In each turn, you attack the monster by applying quantum gates. Your goal is to reduce the state to all 0s. A measurement of 1 or the time running out will result in Game Over.
- **Battle of Millenniums:** The Deutsch–Jozsa algorithm run on a function of your username determines whether you fight for the Angels or the Devils. You have three attacks of varying strength in superposition with a healing action. You also may use a magic attack
- if you have the magic points available. Your goal is to reduce the enemy to zero health, but damaging the enemy also gives them magic points. Bonuses are awarded according to the outcomes of Grover's algorithm and arithmetic operations in quantum Fourier space.

- **Quantum Uno:** A quantum version of the popular card game, Uno. Each card is implemented as an oracle for Grover's algorithm. Superposition cards take the place of Wilds, Entanglement cards act as a sort of delayed Skip, and a whole new Add Phase card rotates the state of the deck.
- **Quantum FPS:** This is a first-person shooter style game in which health is given by the computational basis representation of a 3-qubit state. Hadamard and CNOT gates act as ranged attacks, and X gate is a close-range attack. You can change your own state using H or CNOT on yourself. You can measure yourself or your enemy, but you die if your state is ever measured as j000i.
- **Quantum Invasion:** Player 0 and Player 1 compete for territory across a neutral zone that starts in superposition. Each player has a number of actions to spend on different attacks such as rotating a single qubit, rotating multiple qubits, and entangling target qubits in superposition. At the end of the game, the state of the board is measured, and the player with more qubits in their state wins.

5.Pilot Project QUTE4E

Storytelling in quantum outreach is crucial given the unintuitive nature of quantum mechanics and extremely timely for the potential effect that quantum technologies may have on future society. Counterintuitive examples of quantum phenomena provide engaging platforms to practice the process of scientific thinking with the general public using experimental, creative, and formal literacies. QT also allows educators to integrate Responsible Research and Innovation (RRI) dimensions into a given outreach activity.

The pilot project Quantum Technologies Education for Everyone (QUTE4E) was conceived to respond to the above challenges by building tools to address and measure what aspects of QT outreach and education should possess to be efficient and effective.

The key concept of QUTE4E is that engagement is a fundamental requirement of education, regardless of the learner's technical skills, age, or socioeconomic background. Thus, the goal of the pilot is to design basic and engaging storytelling of the essential concepts in a captivating and language-accessible manner to educate intuition and boost creativity for every target audience: public, students, educators, school and academic teachers, outreach experts, QT companies, or policymakers. Building on this basic conceptual map, the pilot is developing formal language tools with increasing levels of complexity and technical content according to the audience's degree of formal education or educator training.

In the following, we describe how these challenges are addressed by the pilot efforts, via an example on the storytelling of light. Light is a transversal concept in physics, and its concepts are taught in subfields of physics ranging from quantum mechanics to cosmology. The story of light and photonics provides a means to engage with a broad audience as it can be tuned from basic concepts, such as an explanation of how rainbows are formed and why the sky is blue, to specialized technical fields such as quantum optics that directly impact quantum technologies. In addition, because light is familiar to everyone, describing some of its intriguing

properties can also encourage curiosity regarding what is behind the concept of light and how to apply it in our daily life, fostering an interest in science and its applications.

Thus, we believe that teaching through storytelling is the right tool to ignite passion and bring excitement and engagement about nature, and, more specifically, the world of quantum technologies. This method allows the audience to take an active role in searching for the explanation for a previously misunderstood observation, exercising scientific thinking, and exploring new forms of literacy.

In addition, this approach is particularly applicable to gamified and interactive activities that support the active role of the learner in a natural way by introducing relevant concepts through increasingly difficult challenges and levels, creating natural environments for visualization and player experimentation, and providing feelings of success that can foster increased motivation for further education in quantum physics and technology.

The QUTE4E group is designing a general format for storytelling in quantum science and technology that makes full use of the process of scientific thinking.[183] This format starts from observation to create understanding and is then formalized and finally benchmarked back into fact-checking. In this process, the experimental and formal literacies that are required to perform the different steps are built using interactive tools such as those described in this work. Examples include virtual experimental labs and quantum games, popular science animations, and artistic immersive experiences. Once the functional scientific thinking process is scaffolded, one may ask whether engagement is generated through the storytelling of basic quantum science and technologies. In fact, our answer to this question runs along two different dimensions: an educational consideration and a RRI analysis.

Finally, we strongly believe that our storytelling should be guided by and articulated within the RRI dimensions, i.e., public engagement, open access, governance, gender equality, ethics, and science education. The QUTE4E group is developing outreach concepts with a strong focus and involvement of the stakeholder groups to identify the current needs and to respond with innovative solutions.

The pilot resources are conceived to be dynamically updated from existing ones. A nonexhaustive list of existing resources developed by the participants to the pilot consortium includes the following: quantum games with a purpose of education (as in ScienceAtHome, QPlayLearn), also developed in Quantum Games Jams and Hackathons, quantum physics labs (e.g., Quantum Composer, Virtual Lab by Quantum Flytrap, 3D space, Labster[196]), quantum concepts labs (Quantum Composer), quantum algorithms labs (IBM Quantum tools/ Qiskit, Quantum Odyssey), quantum computing resources (IBM Quantum/ Qiskit), educational tangible objects for K12 experience activities (Trump cards at Birmingham[197,198]), quantum pills and animations (QPlayLearn, Quantum Tour[199]), artistic (visual, audible, and touchable) immersive experiences (e.g., Quantum Garden, Quantum Jungle[200,201]), and online courses for different types of beneficiaries (QWorld, QPlayLearn, IBM Quantum/Qiskit). A selection of these was discussed in Sec. 4.

Within the bounds of the pilot, a special emphasis is planned on developing methods of extending the “reach” of a given initiative. Many (already existing) resources lack the proper channels and means to disseminate and be used widely by their potential beneficiaries. As the pilot develops its tools, it can also develop/improve means of reaching target audiences, looking for strategies aimed at making the resources suited to diverse users. Basic outreach activities (such as opening social media accounts or creating online content with no focus on dissemination) are insufficient and fail to reach a wide population. Therefore, the pilot utilizes a wide range of collaborations, together with the informed feedback from a Delphi study, to create, test, and improve a network of dissemination for quantum education-related materials, which will be beneficial to the entire community. Overall, the pilot represents a backbone on which the diverse resources created by the partners can be synergistically made available to boost outreach and education.

In summary, the planned actions include the following. First, we will produce the production of an essential syllabus of quantum physics concepts and their main applications to quantum technologies, identifying for each the type of beneficiary, already-existing educational resources and a list of the missing ones, the learning outcomes, the best-suited type of symbolic/language system, relevant assessment tools, and, coherently with the RRI dimensions, potential applications that the pilot can focus on including public health, the environment, and communication. Second, we will conduct a Delphi study with QTEdu participants and associated parties aimed at identifying stakeholders, opportunities, and problems in QT outreach and engagement activities, as well as practical solutions. The study outcomes are expected to represent a guide for future design of outreach and educational resources that can be disseminated to diverse and extended audiences. Third, we will organize joint outreach virtual activities, including live panels for the European Researchers’ Night, hackathons, quantum game jams, showcases for games and virtual experimental, and simulation platforms and a joint program of events for the World Quantum Day. Finally, we will focus on the assessment of the coherence of the pilot deliverables with RRI dimensions, which is achieved by defining a checklist for each individual dimension and specific type of resources and activities that define the six-by-six matrix described above, and finally applying the checklist to the pilot deliverables. This checklist will be produced via a planned RRI training activity for PhD students from different disciplinary areas. Via this synergetic action, QUTE4E aims to both assess its internal RRI coherence and, at the same time, provide an RRI measurement tool for education and outreach in quantum physics and technologies.

6.Conclusion

In this article, we introduced a wide range of quantum games and interactive tools that have been used across the community for several years for QT outreach and education. Subsections on these tools were written by their developers for them to describe their work in their own words, to share their experiences from the field of games/tools development for outreach and education purposes. In addition, we covered examples of two different types of activities, quantum game hack- athons/jams, and semester projects for quantum game development. Finally, we described the QUTE4E pilot project under the QTEdu Coordination

and Support Action within the European Quantum Flagship Program as an example of how utilization and development activities of such tools can be integrated with quantum outreach and education efforts. These examples were provided to give readers guidance in formulating creative projects and to enhance institutions' capacity to launch pioneering initiatives.

The wide range of games and tools provided here cannot be evaluated from a comparative point of view due to the lack of comprehensive assessment tools in the literature. It is important to develop approaches to evaluate the performance efficiency and effectiveness of the games and tools presented here. The challenge lies in identifying the purpose and scope of their use as they address diverse needs in education, outreach, and research.

The quote "Quantum computing is a marathon not a sprint"[202] is widely used within the community. It is important to add here that this marathon is one that has significant implications for the future of technology and its impact on society.[13,15] Hence, the widest possible participation and engagement by the stakeholders within society should be targeted. We hope that the illustrative examples provided in this article, including games, tools, events, and models, can serve as a solid departure point for current and future practitioners of quantum outreach and education.

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Article 1.6: A Chronicle of Quantum Technologies in Game and Software Development[91]

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Abstract—The ongoing second quantum revolution, marked by advancements harnessing quantum phenomena, has permeated various fields, including communications, computation, and networking, collectively known as quantum technologies (QT). Quantum computing, a focal point within QT, has led to the emergence of quantum games, a novel research and development area exploring creative applications of quantum computing in game development. While more than 300 quantum games have been developed by enthusiasts and commercial parties, a comprehensive research program or state-of-the-art review is notably absent. This paper addresses this gap by conducting a thorough literature review, presenting current advancements and examples in quantum games and interactive designs, and exploring future prospects for quantum technologies in game development practices.

The anticipation of the second quantum revolution, characterized by the development of new technologies leveraging the control and manipulation of quantum phenomena, is impacting numerous fields of technology and science. These efforts span communications, computation, networking, sensing, simulation, and metrology, collectively referred to as quantum technologies (QT). There are more than 30 national and regional initiatives around the globe committing over a total of $38b public spending to the combined QT efforts by 2030s and more than 400 QT start-ups founded, mostly in the last decade [1]. Such levels of investment, and the growing interest in QT due to strategic reasons, QT being categorized under critical technologies by both the EU[92] and the US[93] causing it to be subjected under tighter export controls and investment screening regulations, and with organizations such as the European Commission and NATO coming up with their quantum strategies[94], there is a considerable interest towards the field. Within the more general ecosystem of QT, quantum computing as a research field and the development of quantum computers by private companies as

[91] https://www.computer.org/csdl/magazine/cg/2024/05/10645064/1ZDRi1JhJ0A
[92] *M. Riedel et al., "Europe's Quantum Flagship initiative," 2, Quantum Sci. Technol. 4(2), 020501, IOP Publishing (2019) [doi:10.1088/2058-9565/ab042d].*
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[94] *NATO's Quantum Technologies Strategy: https://www.nato.int/cps/en/natohq/official_texts_221777.htm*

commercial products received distinctive attention by several industries, resulting in formation of industrial consortia in several EU countries, the US, India, Japan, and others. All these led to a rapid expansion of stakeholders within the QT ecosystem [2].

Game and software developers have expressed growing interest in utilizing their creative powers in the search of new ways of using quantum computing [3]. A new research and development area called quantum games (not to be confused with quantum games of extending game theory to quantum rules and strategies) is being formed in recent years. In the literature, quantum physics referencing games have been defined as quantum games quantum technologies; games might have perceivable aspects of quantum physics in them as visuals, narrative design, or through actions defined by game mechanics; they might serve the purposes of science research or education in quantum physics; or even connect to quantum computers and simulators [4], [5], [6]. To date, well over 300 quantum games[95] have been presented in public and the incorporation of quantum computing in game development has also started to attract many professional developers [4].

Although this new topic of quantum games and game development has been gaining attention, with several hundred quantum games being already released, no clear research program or a state-of-the-art review on the topic exists. In this paper, we aim to remedy that gap and review the existing relevant literature (Section 2), present the current state-of-the art regarding quantum games and other interactive designs via some examples that the authors have been directly involved with (Section 3) and discuss the future prospects of quantum technologies and quantum simulations in game development processes (Section 4). We present our findings and conclusions (Section 5 and 6) as an invitation to all software developers, game developers and anyone interested in testing out the latest technological advancements in their respective projects and fields of interest.

2.Navigation the Game Development and Quantum Technology Landscape: Synthesis of Previous Studies

The inquiry on the intersection of game development and quantum physics research is an increasingly active field [4], [7], [8]. In this section, we provide literature reviews on the subjects of the current stage of game development tools and practices (Subsection 2.1) and the literature on quantum game development and quantum games (Subsection 2.2).

2.1 Literature on Game Development Tools and Practices

The game development pipeline is a complex endeavor with a vast number of components such as narrative, mechanics, levels, difficulty, user interface, audio, AI, and many more [9]. The narrative component of game development involves creating coherent stories with interactive gameplay to create immersive experiences. The story helps players emotionally connect to the game, provides context for the players' actions, and enriches the game world with lore and

[95] *The list of quantum games - https://kiedos.art/quantumgames- list/. Accessed: [21 February 2024].*

character backstories [9]. The development process of the story involves character development and creating the theme and lore for players to engage more deeply with the game world. Frameworks such as the three-act structure[96] and the hero's journey help develop a coherent and engaging story [10], [11], [12].

Modern game engines support scripting dialogues, cutscenes and narrative branching systems, helping game and narrative designers to bring their vision to life. In linear narratives the player follows an already designed sequence of events without being able to modify how the narrative unfolds, and in an interactive narrative the player's decisions can lead to multiple outcomes [9]. Interactive narratives offer a more personalized experience to players. However, this approach requires careful planning to ensure that all alternative narratives are meaningful and work in coherence with gameplay mechanics. Otherwise, the alternative endings and/or cutscenes may break immersion, or gameplay may feel repetitive and less meaningful for players. Another component of game development is level design, which usually begins with outlining the level objectives and setting the level's theme and how to utilize gameplay mechanics. Sketches of the level layouts help determine the level flow, setting the groundwork for game development. Level design sets the game's pacing and balance for an enjoyable experience. Having a well-balanced difficulty in games is important, as it is one factor that affects players' focus and keeps them in the flow[97]. To maintain a balanced level of difficulty, some games dynamically adapt the difficulty of the game according to the player's skill[98]. Incorporating story elements into the level design gives the gameplay more depth and context. Game mechanics, visual style, and other aspects of the game should seamlessly work with the story elements and with each other to enhance the immersion.

Methods such as procedural content generation (PCG), the creation of diverse content through algorithms rather than the manual parameter setup, can be used in level design components to enrich the gameplay [13]. "No Man's Sky" and "Minecraft" are two popular examples that showcase the potential of procedural content generation in video games, which is used to dynamically generate terrains and ecosystems with endless possibilities[99]. This method aims to ensure every playthrough is different from each other and increases the game's replayability.

Game aesthetics/game art is an important component in setting the game's atmosphere and shaping players' emotions. Game art enhances the game experience by creating an immersive game world and helping players connect with the game to create the game's visual and sensorial identity. New technologies enhance the impact of game art in the games with more

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[99] *J. Togelius, G. N. Yannakakis, K. O. Stanley, and C. Browne, "Search-based procedural content generation: A taxonomy and survey," IEEE Transactions on Computational Intelligence and AI in Games, vol. 3, no. 3, pp. 172–186, 2011., J. Togelius, N. Shaker, and M. J. Nelson, "Introduction," in Procedural Content Generation in Games: A Textbook and an Overview of Current Research (N. Shaker, J. Togelius, and M. J. Nelson, eds.), Springer, 2015.*

realistic, aesthetically pleasing art. Real-time ray tracing is one of the methods that create highly realistic visuals, amplifying the games' environment and atmosphere. By simulating the physical behavior of light, ray tracing enables realistic effects such as reflections and shadows to make the game environment more realistic [14]. Popular game engines such as Unity3D and Unreal Engine integrate ray tracing methods into their engine so that developers can easily utilize them in their games.

The visual quality enhancements of games usually come at the cost of reduced performance. This trade-off can be crucial, especially for genres such as shooter games where reaction times are essential and affect the player's enjoyment and performance. Different ray tracing techniques have been developed to get better results in terms of performance and quality. Another promising solution for better performance is using deep learning for super-resolution, an algorithm that allows games to run at lower resolutions and upscale them to higher visual qualities. NVIDIA's Deep Learning Super Sampling (DLSS)[100] is one of the latest examples of this technology.

User interface (UI) components of games are design elements that provide information about the game state to the players. The interface design should be user-friendly and show necessary information, without any elements overwhelming the players' experience. They are usually in 2D format, on the screen separated from the game, but they can also be in 3D. Since the sense of presence is really important for immersion in Virtual Reality (VR) games, 3D interfaces are found to be more realistic and have the potential to be more effective[101].

Animations are used in games to make the objects in the game move in a specific way. These objects can be characters, environmental props, or special effects. Animations bring life to the game, making it fluid and dynamic. However, creating realistic animations, especially for human-like movements, can be challenging. To create more realistic animations, motion capture technologies are used to record detailed motions in real-time. By equipping a special suit with infrared markers, performers simulate the action that will be used in games. Cameras positioned around the performer capture the performer's motions and the surrounding volume is used to reconstruct those movements in the digital world for a more realistic representation. Procedural animation algorithms can also be used to dynamically change according to the environment or adapt to specific gameplay choices of action.

Games may have multiplayer components that enable online interactions between players. These interactions add another layer to the game mechanics by making the games generally more interesting and challenging than playing against non-playable characters (NPCs)

[100] *Nvidia Deep Learning Super Sampling (DLSS): https://resources.nvidia.com/en-us-game-devdlss/how-to-successfully?ncid=no-ncid*
[101] *S. Safikhani, M. Holly and J. Pirker, "Work-in-Progress—Conceptual Framework for User Interface in Virtual Reality," 2020 6th International Conference of the Immersive Learning Research Network (iLRN), San Luis Obispo, CA, USA, 2020, pp. 332-335, doi: 10.23919/iLRN47897.2020.9155207*

controlled via AI[102]. Multiplayer games can have systems such as matchmaking and data synchronization. These systems are hard to implement because the risk of waiting too long for matchmaking can make players quit, or too long of a delay in network transmission can cause unfairness. Game engines provide solutions such as NetCode by Unity3D and Replication by Unreal Engine to ease the implementation process of multiplayer mechanisms for developers by providing high-level features. Games may often have multiplayer components and contain AI-controlled NPCs. These NPCs can perform complex decision-making processes using methods such as behavior trees as well as move with pathfinding algorithms such as A*. However, compared to the real players, NPCs can decrease gameplay immersion if the NPCs behave unrealistically within the game world. Machine learning can be a solution for creating believable AIs by using methods such as generative models to simulate more fitting behavior.

Input controls are another game component defining the medium the player interacts with the game. This interaction can be done through a keyboard, mouse, gamepad, touchpad, virtual reality controllers or hand-tracking interface. It is important that the controls in the game are responsive and effortless for the game experience to feel sensible. Controllers should also be customized to make the game more accessible between different control modes. Game engines usually provide their own input system for adjusting input mapping and switching between different types of controls.

2.2 Quantum Computing for Game Development

Quantum computing platforms such as those offered by IBM, Google, and Microsoft offer online access to quantum computers[103]. Through these platforms, the computational power of quantum computers is accessible to a vast range of professionals, including game developers. Specific software and game engines dedicated to quantum game development, and expansions for game engines such as Unity3D have been introduced through open access sources [4]. Quantum computing software can be used to simulate quantum systems and implement quantum algorithms, which potentially have capabilities more powerful in certain tasks than what can be achieved with classical computers.

So far not many games connect to quantum computers directly due to existing technical hurdles of quantum computer access, but many claim having used quantum simulations either in the development of a game or implement the simulations directly in the game play [4], [15]. The first game on a quantum computer was developed in 2017 and was used through a terminal interface [4], [15]. Since then, the incorporation of quantum simulations and quantum computers to game development has gained popularity through open game development events such as game jams and hackathons, particularly since the release of the quantum software development tool Qiskit by IBM and multiple Qiskit-themed hackathons and game jams [16], [17].

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[102] *Dardis, F. E., and Schmierbach, M. (2012). Effects of Multiplayer Videogame Contexts on Individuals' Recall of In-Game Advertisements. Journal of Promotion Management, 18(1), 42–59. https://doi.org/10.1080/10496491.2012.646219*

[103] *IBM Quantum: https://www.ibm.com/quantum, Google Quantum AI: https://quantumai.google/, Microsoft Quantum Computing: https://quantum.microsoft.com/*

Game jams are local, regional or even global events for individuals and teams to create games during a set period of time, either experimenting or learning new tools, technologies, or creative practices, as well as engaging in interdisciplinary creation. There is usually an event-specific theme upon which participants are encouraged to use as the main topic for their games or as inspiration. For example, Quantum Game Jams (QGJ) are considered as such since games made during the jam are expected to be in some capacity connected to quantum physics [16], [17]. The relation to quantum physics can be purely conceptual, or it can include direct scientific implementations, the use of quantum technologies, or simulations [4].

The origins of QGJs are in citizen science (CS) games and educational games for learning quantum physics and quantum technologies [16], [17], [6], [18]. With its initial cause in scientific and research development, the QGJ has grown into a global event, which has also been the first ever game development event with access to quantum computers and tutoring on quantum computing [16]. The participants in QGJs have become more diverse throughout the years, including visual artists, writers, and musicians who have no direct contact with quantum physics or game development prior to the event by occupation or personal interest but are simply intrigued by the opportunity to contribute with their own vision and have a joint creative experience [17].

CS games extend an invitation to the general public, encouraging active participation in scientific research projects. These games harness the collective intelligence and problem-solving skills of players to address the research question(s) at hand. By merging game design principles with scientific tasks, these innovative platforms effectively bridge the gap between research and real-world applications. CS games find particular suitability in the realm of quantum physics, where abstract concepts are often difficult to convey without mathematics or traditional representation methods and has led to the development of numerical visual simulators [3], [6], [18].

Often the connection to quantum physics in quantum games presents itself in the inspiration for the perceivable aspects in the games, but quantum mechanical phenomena, such as entanglement, superposition, and quantum tunnelling can also be used to develop novel gameplay mechanics [4]. These mechanics can give players a new perspective and affect how they perceive and play the game world. Examples include various versions of quantum chess [19], [20] and quantum go [21] that utilize the principles of quantum mechanics by building upon classical versions. In the quantum version of these games, pieces can, for instance, move in multiple positions by being in a superposition state, or they can be entangled into different pieces and be affected by measurements simultaneously. This adds unpredictability to the classical versions of the gameplay.

Storytelling aspects in a game may also be incorporated using principles of quantum mechanics to create engaging and immersive experiences. Quantum Break uses quantum physics concepts to ground its science fiction mechanics, such as time travel, with a narrative that

explores its consequences[104]. It complements the gameplay with a narrative that reflects a quantum phenomenon, making the mechanics and narrative coherent.

Interactive storytelling refers to a practice in which the user/player/viewer of the medium takes active participation in shaping the experience. Unlike traditional linear storytelling, where the narrative progresses along predetermined path(s), interactive storytelling allows players to choose these paths and get a sense of consequences for their actions that directly shape their experience further. This is why games have a broad impact not just as entertainment media but as tools for cognitive skills development, learning methodologies, social interactions, and well-being. Games allow exploration of the given topic, challenge, or artistic experience in a safe digital environment that can be adjusted for specific needs of the players, especially in cross-platform accessibility. This is why interactive storytelling is playing an ever-increasing role in game design and development of immersive gaming experiences and allows testing of potential uses of other emerging technologies and design principles, such as QT [8].

The use of quantum computing procedural generation techniques offers promising potential in creating vast, complex game worlds [4]. While quantum algorithms theoretically have the potential to process an extensive amount of data in certain processes faster than classical computers, the practical use of quantum applications is still in the early development stages. Quantum computing principles can already be applied in game development to create dynamic graphical and environmental iterations through a method that uses quantum interference in creating a unique blurring effect [22].

Due to algorithmic generation methods, the randomness generated by classical computers is not truly random. The methods used to get random numbers in classical computers are often seeded by environmental factors such as mouse movements or computer time, to break possible repeating patterns in the output [23]. For quantum computers, generating a truly random number is possible. Processes such as measuring a qubit in superposition result in outcomes that are fundamentally unpredictable and access the inherent randomness of quantum physics. Quantum randomness can be used in-game mechanics where randomness is important to ensure that these mechanics are truly unpredictable [24].

The integration of quantum computing with game development, facilitated by platforms from IBM, Google, and Microsoft, and with access to a wide range of simulators, has enabled the creation of games that incorporate quantum physics principles. These advancements have been particularly evident in the rise of QGJs, which encourage the development of quantum-inspired games by a diverse group of participants. Such games explore novel gameplay mechanics and narratives grounded in quantum mechanics, offering players unique experiences.

[104] *M. Kamen, “How real physics impacted time travel game quantum break.” https://www.wired.co.uk/article/quantumbreak-interview-sam-lake. Ac- cessed 20 February 2024.*

3.Examples of Quantum Integration in Games

In this section, the authors elaborate on their learnings and experiences on quantum games and graphical user interfaces (GUIs) for quantum computing software and numerical simulations they have been involved with: C.L.A.Y., QWiz, and Pulser Studio. With the constantly evolving landscape of QT, we find ourselves at the nexus of research and practical application. The collaborative spirit among research groups is palpable, with diverse approaches converging under the umbrella of quantum software development. The following sections unfold against the backdrop of this dynamic synergy, as we explore the various methodologies that have surfaced through ongoing research and market-driven projects.

3.1 C.L.A.Y., QWiz, and Pulser Studio

One of the first attempts in commercial quantum game production was done in 2020-2021 by MiTale, a team of game developers from Finland, together with a research group from IBM in Zürich [4], [8]. With the game project “C.L.A.Y. - The Last Redemption” they have taken a step forward and experimented with the possibilities of integrating quantum technology into the interactive storytelling design and narrative progression of a game. This role-playing game (RPG) is set in the post-apocalypse several generations after the collapse of civilization. Such a narrative setting allowed the developers to experiment with quantum simulations in multiple aspects of game design and development, such as generating environment and visual effects, character development and in-game relationships and branching narrative and encounters. QT has been tested in the following features of the game (see Fig.1):

- Generating environment and visual effects: Procedural generation has a leading role in environment and visual effects in the game based on quantum computing technologies by IBM’s team of researchers led by Dr. James Wootton [22].
- Character development and in-game relationships: Quantum physics is implemented with in-game characters, developing personalized relationships with the player’s lead character based on the type of game the player pursues. Each movement, dialogue, and action or not taking action are deeply seated with the narrative side of the game, providing unique twists and outcomes for each quest.
- Branching narrative and encounters: As a narrative-driven RPG, the choice-based narrative is an obvious place in which quantum simulation can be used. The quantum effect on the narrative progression can result in many more possible endings with the same “choice” that the player may make.

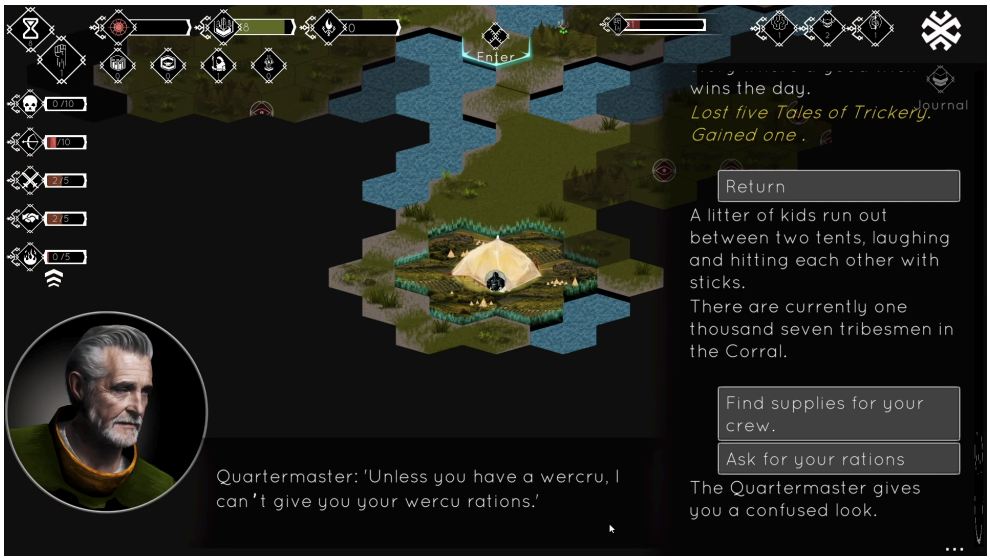


FIGURE 1. Screenshot from the game "C.L.A.Y. - The Last Redemption, the use of Qiskit in map/exploration mode

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While the research work is ongoing, the initial gathered results from MiTale's team and their players indicate a vast potential for using quantum computing by game designers in interactive storytelling design practices [8].

Furthermore, storytelling is just one part of the bigger design pattern the game designer can use to craft an immersive experience. Game design comes first, in which the designer sets the challenges and core mechanics. No amount of good story or impressive audio-visuals can compensate for poor game design choices. The embedded story, visuals, and other game aspects must follow game design principles. This is why quantum computing needs to be accessible to game designers and other game industry professionals so that they can explore the full potential in which quantum technologies can be utilized in the user-centered design of games. It remains a challenge that quantum technology is overly expensive and not fully accessible, as quantum computers are a rare commodity for most of us.

Quantum computing presents its own set of challenges for game designers to tackle. These challenges compel designers to step out of their comfort zone and known best practices, venturing into the development of new ones that incorporate quantum technologies as a new asset in game development. On multiple occasions, game developers have been involved in creating citizen science games for various disciplines and research purposes, including quantum physics and computation.

Games and interactive experiences can provide an immersive three-dimensional environment that amplifies the sense of presence, empowering players to explore abstract and challenging principles on their own terms. An exemplary illustration of this approach is the virtual reality (VR)

game “QWiz - Quantum is Magic”[105], (see Fig. 2) a collaborative creation by the game development company MiTale and the Turku Quantum Technology (TQT) research group at the University of Turku [3], [18]. VR technology seamlessly integrates players as active participants in the digital realm, with spatial interactions closely mirroring those of the real world. This functionality allows for the direct manipulation of surroundings, faithfully replicating immediate consequences for actions.

In QWiz, players assume the role of a “quantum wizard apprentice,” learning about quantum phenomena visualized as a liquid that adheres to the laws of quantum mechanics. The game utilizes the “Quantum Black Box”[106], a numerical simulation of a quantum control optimization problem, developed by TQT, operating in real-time in both VR and web-based versions of the game [3], [18]. By creating a visualization of quantum phenomena in VR, players can dynamically adjust parameters and observe quantum effects, intuitively understanding the challenges and improving their mastery with each attempt. Simulating quantum experiments in VR settings has shown excellent preliminary results, particularly among young children. In addition to offering a way to enter the world of quantum mechanical behavior, QWiz has served as a citizen science game, collecting data from player interactions to help address topical research questions without requiring prior physics knowledge [3], [6], [18].



FIGURE 2. QWiz VR environment

Beyond quantum games, there are examples of graphical user interfaces (GUIs) for quantum computing software. Pulser Studio by Pasqal (pulserstudio.pasqal.cloud) is a web-based no-code platform for neutral-atoms programming, created by the Quantum Flytrap team. While it is not a game but an introductory prototyping tool for quantum computing, we note that the design obstacles are similar to those in the development of GUIs for quantum games.

[105] *QWiz – Quantum is Magic, WebGL port: https://qplaylearn.it/game-qwiz*
[106] *Quantum Black Box - open source by Dr. Matteo Rossi; https://gitlab.utu.fi/matros/quan-tum-black-box*

One of the challenges the creators of the Pulser Studio faced was users' lack of "quantum intuition" or established mental models when it comes to quantum computing and visualizing quantum phenomena. Mental models mean that the interface feels familiar, which eliminates the need for a lengthy introduction to how to use the tool. In the Pulser Studio, the creators tackled this by using analogies from other disciplines and translating them into a quantum computing interface. For example, a feature for designing pulse sequences (see Fig. 3) was designed to remind common sound editing software. Typically, such software features channels with blocks of sound waves that can be horizontally rearranged and customized by the user. In Pulser Studio, users work with channels containing blocks with waveforms representing light pulses. The overall usage of the software is different, yet on the level of a specific feature, the interaction and UX are similar.

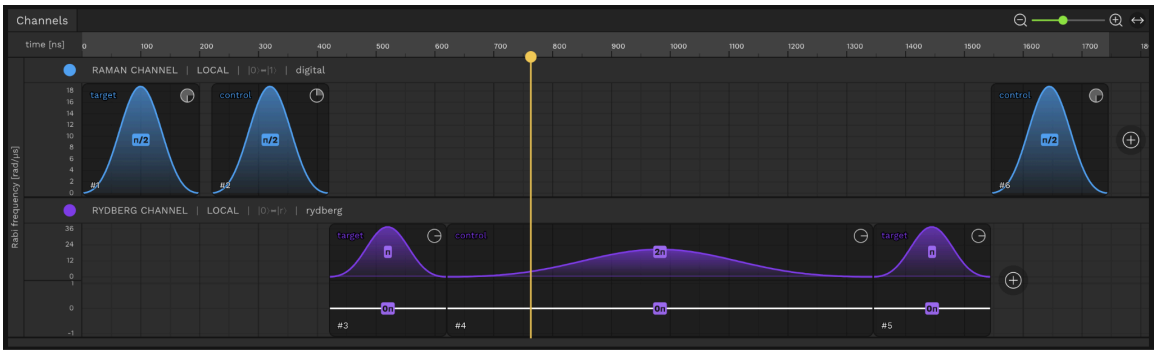


FIGURE 3. Channels feature from the Pulser Studio by Pasqal, used to design pulse sequences. Control-Z Gate example

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The shared vision of these projects is to enable players to play and explore real and numerically simulated quantum phenomena, mastering skills through puzzle-based gameplay without requiring any previous experience or knowledge in quantum physics. These types of projects provide an excellent start in engaging common players with quantum technologies, creating awareness and popularizing the field of quantum games.

3.2 The Current State of Quantum Game Development

The results of quantum physics themed game developing events, for example QGJs, have been valuable for scientific communities and researchers in solving specific quantum physics problems, but they have not yet shown any significant advantages for software and game developers considering replacing classical computing solutions in games. In most cases, quantum simulations have been broadly tested by game developers as a more advanced "random event generator," which can be an exciting feature for a developer but does not make a significant difference in players' experiences [16]. Game design, in particular, is driven by a player's expectations and experiences that the designer carefully crafts through user-centered design practices. Therefore, if a feature or, in this case, quantum technology does not directly contribute to players' experiences or expectations, it does not have a value proposition that a designer would consider for use.

Another challenge for game designers and software developers is the limited use and accessibility of quantum technology (including simulations) without prior physics or advanced mathematics knowledge. Looking into the practical needs of game developers, commercial game development is a fast-paced process in which every game requires rapid iterations and testing, shaped by the chosen genre, platform, used technologies, and most importantly, feedback from the players. In such an environment, developers are looking for solutions that would ease their workload and possibly make some processes perform faster, not necessarily to start learning quantum physics and implement tools that are not comprehensive for non-physicists. Open-source simulations, such as Qiskit by IBM, are great tools for developers to get familiar with the potential uses of quantum technologies, yet the direct use, as well as user interfaces, are in Python code and add an extra layer of accessibility challenge for game designers who do not necessarily have any coding experience. To make quantum computing more accessible for software and game developers, it is crucial to have close collaboration across these disciplines, where different professionals with diverse sets of expertise would test and develop new solutions for utilizing quantum simulations and computation specifically for its use in games.

We are still in the early stages of integrating quantum technologies with market-driven game development; however, there are significant efforts from industry professionals and scholars working on possible new solutions for easier integration. Until we have more accessible quantum software interfaces, educational efforts play an important role in building an informed society [25]. Besides game jams and hackathons, there are individual projects that serve both entertainment and education, such as “Quantum Composer” by Science at Home, “Hello Quantum” by IBM, “Quantum Game/Virtual Lab” by Quantum Flytrap and “Quantum Odyssey” by Quarks Interactive [26]. All of them are designed as commercial products that also serve the public with a scientific understanding of quantum physics.

Quantum-inspired algorithms leverage some principles of quantum computing without requiring a direct connection to the quantum computer. Running on a classical computer, these algorithms allow game developers to explore the opportunities of using quantum technologies in game design and production more deeply. While such games can already be fully developed as market-ready products, such as C.L.A.Y. - The Last Redemption [8], it does not necessarily mean that they would function the same when connected directly to an actual quantum computer. This means that the results of simulations can be entirely different from what they would be if the game were connected directly to the quantum computer due to additional “noise” and technical requirements (e.g., a steady connection).

There is a high level of uncertainty regarding the expected results of a game made with a simulation and intended to work directly with quantum computer integration. One practice is to have occasional connections assembled between the game and the quantum computer, even for a short period, such as several seconds, and then let the game run further on a classical computing system. This way, developers can evaluate and better estimate the game design and technical adjustments needed for the final gameplay experience utilizing quantum computing. Limited resources and access to available quantum computers challenge this approach.

4.Envisioning the Future Directions of Quantum Technologies in Game Development

In this section we present our insight into the future prospects of combining quantum technologies and quantum software into game development procedures. We see that one of the most promising and near-term achievable ways for game development to benefit from quantum technologies and quantum software is through Quantum Visual Computing (QVC).

Grover's search algorithm is one of the most well-known examples where quantum computing improves on classical computers, offering a quadratic speed up. It performs a search for an item from an unsorted list. While a classical search algorithm would require O(N) steps to search through an unsorted list of N items, Grover's algorithm can achieve this in $O(\sqrt{N})$ steps. This speedup becomes important in rendering and geometry processing, where searching and optimization are the core operations [27]. The algorithm can be used in quantum rendering algorithms such as quantum ray tracing to utilize quantum mechanics concepts such as superposition and entanglement to render complex scenes[107].

An example of Grover's algorithm is Z-buffering, which is a visible-surface algorithm that checks the Z value for each pixel of all polygons in the scene. The polygon with the highest Z-value is rendered on the screen. While this is not exactly a search problem, Grover's algorithm can still be used to find the element with a minimum value in a dataset. For each pixel on the screen, a uniform quantum superposition of states can be created where each element points at a polygon in the database. The distance between the polygon and the pixel gives the Z distance [27]. From there, Grover's algorithm reduces the computational complexity from linear to quadratic, offering a more efficient rendering process for complex scenes.

Global illumination is another feature that games use to create realistic environments, and the radiosity technique can be used to compute global illumination in scenes. In radiosity, the pixel's color depends on the collection of radiosities at the corresponding point on the scene. The emitted energy summed with reflected energy for a point on the scene gives the radiosity. Techniques used for Quantum Z-Buffering and Quantum Ray Tracing can also be used for the Quantum Radiosity algorithm to reduce the complexity $O(N^2)$ of the classical task to $O(N^{3/2})$ [27]. While the theoretical framework suggests significant improvements in computational efficiency, the practical use of Quantum Radiosity is still yet to come. In classical computers, the method for supersampling sub-pixels in rendering is generally done by Monte Carlo integration and is used in ray tracing. Introducing the quantum variant of this method is called quantum supersampling (QSS). A comparison of QSS with classical Monte Carlo integration was performed with simulation experiments and demonstrated that QSS is better at reducing mean pixel error. However, experiments made on actual quantum computers were not as successful as simulations due to the noise in the quantum computers[108].

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[107] *L. P. Santos, T. Bashford-Rogers, J. Barbosa, and P. Navr.til, "Towards quantum ray tracing," 2022*

[108] *E. R. Johnston, "Quantum supersampling", SIGGRAPH '16: Special Interest Group on Computer Graphics and Interactive Techniques Conference, Association for Computing Machinery New York NY United States, 2016*

Another method is with the algorithm for binary image filtering called the Quantum Coin (QCoin)[109], which, compared to QSS, works better on both simulators and actual quantum computers. QCoin is a hybrid algorithm that has both quantum and classical parts. This helps QCoin to work better in the presence of noise and offers more practical advantages than QSS[110]. Recently, the QSS algorithm was improved compared to classical and quantum ray tracing on a 3D scene rendered using Blender cycles. Results showed that the improved quantum approach created better image quality than classical ray tracing [14].

In the current state of game development, technologies such as procedural generation and rendering are already used [28]. Quantum technologies have the potential to enhance these technologies using quantum algorithms providing true randomness and other features that can inspire new gameplay mechanics. This convergence of quantum computing and gaming not only enriches the gaming landscape but also serves as an innovative platform for testing practical implementations of quantum technologies as well as educating and engaging with quantum physics concepts.

4.1 Tools for Utilising Quantum Technologies in Games

By examining the presented case studies and preliminary results from each of the projects, we can see that the integration of quantum computing and gaming technologies holds exciting potential, especially for the future directions in software development. With the emergence of AI technologies and quantum-inspired algorithms, their use for game AI and non-player characters (NPCs) can enhance game design practices, providing additional options for dynamic decision-making processes by players and optimize complex branching systems. Real-time quantum integration can support adaptive gaming experiences based on players' interactions in both single and multiplayer settings. Quantum technology holds the potential to enhance user-generated content, modding features and community building. Hybrid quantum-classical gaming systems could seamlessly combine the strengths of both technologies, allowing a limited number of qubits to perform at their full capabilities.

However, with the current quantum solutions and resources available on the market, software and game developers face challenges in understanding which aspects of quantum computation they can utilize and, more importantly, which aspects are most beneficial for the specific features or functions under design and development. When developers embark on creating a feature or game mechanic, the chosen approach is often based on available resources and the time required to complete the task. Integrating quantum software into this process requires developers to possess a deeper understanding of the benefits it brings, both to the development process and the players' experience. Furthermore, clarity on which conditions of the quantum solution should be used and in what manner for these two aspects is not readily available within the current platforms on the market.

[109] *C. Cantwell, "Quantum chess: developing a mathematical framework and design methodology for creating quantum games," 2019*
[110] *N. H. Shimada, T. Hachisuka, Quantum Coin Method for Numerical Integration, Computer Graphics Forum, May 2020*

To make quantum computing more accessible for classical software developers and game designers, a comprehensive tool is necessary, directly serving the development processes. This tool should feature a user-friendly interface, searchable functionalities, and ideally, visual scripting aspects. A research project led by Natasha Skult and Dr. Jouni Smed from the Department of Computing at the University of Turku is currently developing the initial structure of such a tool, named “Naviqate”[111]. It aims to be available for initial testing in early 2025. The tool currently utilizes the Qiskit solution by IBM and will be applicable for game developers using Unity3D, Unreal Engine, and Godot. For narrative designers, the tool is already undergoing testing with Ink, a narrative scripting language for games developed by Inkle Studios[112].

4.2 Addressing the Limitations, User Experience Challenges and Role of a Game Designer in Quantum Game Design

Regardless of the physical systems and specifications of the quantum computers, creating highly accessible QT user experience and interaction design is crucial. Designing interactive experiences requires a multidisciplinary approach, combining creative and technical knowledge, empathy, soft skills, and an understanding of the target users. User experience design, as well as interface design (UX and UI designs), is in the early stages of development for quantum simulations and technologies due to their complexity. Currently, the majority of QT simulations and tools are available in various programming languages, with most accessible through Python code. Ensuring that the same content is accessible to a wide range of users, including those with non-physics or limited coding experience, is highly demanding and not currently offered by any platform on the market.

A specific challenge is providing effective feedback to users about their actions within quantum simulations. The feedback system, as well as guidance on using the tools most effectively, is still in the early stages of development. IBM Q Experience and Classiq[113] platforms provide well-designed graphical user interfaces alongside the programming language, but may still seem overwhelming to many users who are not affiliated with quantum physics. In game development, UI/UX design best practices have evolved significantly due to the necessity for cross-platform compatibility and user accessibility features. By applying inclusive UI/UX design principles from the games industry [9], quantum technology experts can benefit from their insights in solving the visual representations of the complex features these platforms provide. Furthermore, these are iterative processes that require continuous refinement based on user feedback and changing requirements. Depending on the platform, creating user interfaces for quantum technologies requires a deep understanding of the technical aspects involved, including the implementation of frameworks and tools. This ensures that responsive design with a clear visual hierarchy and prioritized readability (font sizes, line spacing, contrast, etc.) will ensure easier navigation and intuitive interaction [9].

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[111] *Naviqate - tool under development by Natasha Skult as part of doctoral research project “Interactive Storytelling with Quantum Computing” at University of Turku, under the supervision by Prof. Jouni Smed: https://www.mitalegames.com/quantumgames*

[112] *Ink by Inkle Studios: https://www.inklestudios.com/ink/*

[113] *Classiq is quantum software platform that enables the design, optimization, analysis, and execution of quantum algorithms, https://www.classiq.io/*

The role of a game designer is a combination of creative, technical, and interpersonal skills, including communication, emotional intelligence, and teamwork. In traditional game design practices, designers are tasked with crafting the overall gameplay experience and addressing specific features and mechanics within the game. In larger teams, game designers may lead a dedicated group handling mechanics, level design, in-game economy, and other aspects falling under game design. In smaller indie teams, a game designer might work independently and may take on additional roles, such as Team Leader. Regardless of the team size, the game designer holds the responsibility of communicating the project's vision and goals to the team, answering questions, and addressing concerns from both the team and players.

Applying traditional game design practices might prove insufficient when working with quantum computing, and thus the role of a separate "quantum designer" has been suggested to accompany game designers and software designers [18]. The specifications of quantum technologies can offer increased computation power and a higher number of content combinations for players to experience. Moreover, the content can be directly adjustable or created by the player, allowing game designers to explore modular game design practices. This approach enables dynamic storytelling with personalized content, giving players actual choices to shape the game world [8]. One of the novel and very valuable advantages in potential use of QT in game design and development is the modular development approach which can enhance the game design choices to be adapted into the gameplay experience along with the possible interactions of the players. The designer's new role becomes one of facilitating these choices, ensuring that consequences are meaningful and contribute to the overall interactive storytelling. This shift resembles the role of a "game master" in roleplaying games, where the game evolves through active contributions from all players in collaboration with the game master.

While the modular game design approach brings exciting opportunities for game designers, it also introduces new challenges. Balancing player freedom with a coherent narrative, managing the complexity of dynamic systems, and ensuring an enjoyable experience for a diverse player base are among the key considerations in this revolutionary method.

5.Discussion

In this paper we have primarily focused on providing a review and projections from within the field of quantum game development to discuss the future prospects of quantum technologies and quantum simulations in game development processes. This is a deliberate choice, one which provides both a degree of freedom for us the authors and several limitations on top of those that arise due to the nature of this topic. First, the extend of literature on (classical) game development is several orders of magnitude greater than the existing literature of quantum game development, therefore making a complete review of game development literature or even a complete coverage of all the game development components is not possible due to the context of this study and the review we provided in Subsection 2.1 should be accepted only as representative and not as an exhaustive one. Second, most common development activities of quantum games and game development efforts utilizing quantum phenomena (particularly

quantum computers) occur either in online communities or in commercial enterprises, and only rarely presented in academic media such as published articles or proceedings. Several of the authors are either personally or via their networks involved with a wide range of quantum game development activities, however, it would be entirely likely that there are efforts that fall beyond what is publicly (or privately) available to us. Therefore, the content provided in this study is mostly representative and not exhaustive this time, not due to the extent of the activities but due to their sparse and non-academic nature.

Finally, our projections on how the future of quantum technologies might impact game development should be accepted as such, projections. Quantum computers and similar quantum technologies that may be relevant for game development are still in their very early stages of development. We do not know whether a future large scale quantum computer will perform on the cloud or on-premise, or whether it will perform on superconducting circuits that require excessive cooling or on ion-trap systems that require entire vacuum systems to operate. These factors directly relate to the potential capabilities (e.g. gate operation times), costs of utilizing such systems for games, and resource consumption of these future devices. Setting out a clear and well-defined research program at this point requires introduction of a series of what-if scenarios that lead to entirely different analyses on hardware levels for the same higher-level game development components and relevant methods (e.g. ray tracing and procedural content generation). Therefore, we chose to focus on the topics we have direct experience in, while also acknowledging that these future directions are mere potential uses, as the truth is, we do not know which physical systems the future quantum computers will operate on.

6.Conclusion

The integration of quantum computing in game development represents a still young field of research and development, which already shows promising unprecedented advancements in simulation, optimization, and immersive experiences. Tracing its historical roots from theoretical concepts to practical applications in this article, the literature review underscores the transformative potential of quantum computing in game development. Current practices showcase early experiments in algorithm optimization and complex simulations, while upcoming developments hold promise for solving intricate problems in AI and procedural content generation.

As the gaming industry starts to get more literate about quantum technologies and vice versa, it stands on the cusp of a new era, where the computational power of qubits opens new opportunities for innovative gameplay mechanics and user experiences. However, challenges such as hardware constraints and algorithmic refinement persist. Nevertheless, the journey from theory to application in quantum game development remains an exciting frontier that has the potential to reshape the gaming landscape fundamentally.

We are at the very early stages of this potential transformation, which may (and possibly will) follow a trajectory which is particularly difficult to ascertain at this point. In this article, we

provided a solid ground for the following research to build upon and provided some speculative future directions that we find promising and fruitful in the not-so-distant future (with some tools such as "Naviqate" already under development). We believe that further research and interest towards the topic is warranted at this point, even if to just expand our classical horizons to get a glimpse of what we can learn and utilize for game development from the microcosmos.

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Article 1.7: Educating to the “Culture” of Quantum Technologies: A Survey Study on Concepts for Public Awareness[114]

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ABSTRACT
In this article we offer a conceptual and practical contribution to the field of STEM education by investigating the concepts educators may include in Quantum Technologies (QT) outreach activities. We embed our approach in the discipline-culture (DC) framework, in which we consider the cultural nuances of QT as an important factor which must not be ignored in education efforts. To this end, a survey study by the pilot project Quantum Technologies Education For Everyone (QuTE4E), investigating key concepts for QT outreach, was conducted between December 2021 and June 2022. Here we present the results of the study, analysed through the DC framework, and consider the implications for designing QT outreach activities. The data hints at the perceived value of highlighting core concepts of Quantum Mechanics (QM), while also raising the question of whether QT sits as a discipline of Physics, Computer Science, or elsewhere. This calls for a reordering of the primacy of certain concepts (such as qubit and spin) for outreach purposes, where core concepts in QM might not be core concepts in QT, and vice versa. The results of this study provide valuable insights for those interested in learning more about this rapidly-evolving field.

Keywords: quantum technologies, outreach, education, public engagement, scientific culture, science communication

Introduction

The Advent of Quantum Technologies

The *second quantum revolution* (Dowling and Milburn, 2003) has been ongoing since the late 90s as advances in our understanding of quantum mechanics, as well as the development of new technologies for controlling and manipulating single/individual quantum systems, have

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been yielding increasing outputs in terms of scientific publications, patents, and start-ups (Seskir and Aydinoglu, 2021; Seskir and Willoughby, 2023; Seskir et al., 2022a). Currently, there are at least 25 enacted national and regional initiatives on QT (QURECA, 2022) with approximately $30B of public funding allocated to the field until 2030. Many in the field now believe that raising awareness is the absolute minimum that needs to be done (Roberson, 2023).

A central problem in raising awareness of emerging technologies such as QT is reaching members of the public, in particular school students, when there is no standard representation of QT in national curricula (Faletic et al., 2023). Those of school age will compose the future quantum workforce, and thus it might be beneficial if they are inspired from early on, that they may begin their journey towards the industry. Furthermore, even those with no future education in STEM fields will live in a society dramatically influenced by QT (Vermaas, 2017), and it is essential that they are accepting of and open to the changes it will bring, rather than suffering from hype and misinformation which could substantially damage how we navigate the modern "society of acceleration" (Rosa, 2010; West and Bergstrom, 2021).

Quantum Technologies Education for Everyone

To this end, increasing efforts are going into the public communication, or *outreach*, of QT worldwide (e.g Italian Quantum Weeks, 2022; World Quantum Day, 2022). Innovative means of bringing quantum physics and technologies out of the lab to public audiences, such as through experimental demonstrations (Gow et al., 2018; 2022; Posner et al., 2018), artistic expressions (Hutchinson, et al., 2015; Decaroli & Malinowski, 2022), games and interactive tools (Wootton, 2017; Cantwell, 2019; Ahmed, 2021; Seskir et al., 2022b; Migdał et al., 2022; La Cour et al., 2022; Piispanen et al., 2022), and other novel methods (Goorney et al., 2022) have been developed as QT are becoming more and more realised.

With more time and energy serving this goal, it is now of essential importance that outreach is taken seriously for what it is - a kind of non-formal education, which may be the best tool we have to address the problems of hype and misinformation (Mackay et al., 2020). Educators and practitioners must be equipped with guidelines and best practices for how best to make use of limited time available in outreach activities. Addressing this need, the project Quantum Technologies Education For Everyone (QuTE4E), a pilot of the Quantum Technology Education (QTEdu, 2022) community initiative, ran for one year between Autumn 2021 and 2022. In QuTE4E, QT educators, researchers, and industry stakeholders have come together under a shared passion for communicating this rapidly developing field to the public.

The goals of the pilot have been twofold. First, it has been to unite the community and draw on the diverse knowledge, interests, experiences, and resources of its participants to pioneer a new approach to outreach we call *Physics Outreach Research (POR)*, based in the field of QT. Second was to utilise this research-based approach to develop practical guidelines and methods which may be used for education outside of the classroom, such as guidelines for quantum science and technologies outreach and a concept inventory for QT outreach. Contributing research in this direction includes a framework for the narrative structure of

activities (Goorney et al., 2022), a compendium of useful tools for practitioners (Seskir et al., 2022b), and an evaluation of outreach activities conducted through the pilot (Chiofalo et al., 2022). One of the research activities was to carry out a survey study to determine the Stakeholders, Opportunities, Problems, Solutions, and Concepts for Quantum Outreach, which ran between September 2021 and June 2022. Here we introduce the findings of the essential Quantum concepts which are needed in informal education activities and present a classification scheme which may be used by educators and practitioners to inform what they choose to outreach. We then consider the implications of these findings for designing and carrying out QT outreach. As the need for informal education in QT increases, and outreach events increase in both number and diversity, this study may help developers and practitioners to increase their impact in this important field.

Speaking the Quantum "Language": The Discipline-Culture Approach

One particularly interesting aspect of QT is its mystifying "culture", particularly with respect to the Quantum Physics which underlies it. Educators have considered this implicitly many times, referring to the unique "language" of quantum physics (Decaroli and Malinowski, 2022; Bouchée et al., 2022). One may consider that as a discipline, quantum physics has its own narrative, including a historical development (Weissman et al., 2018) and numerous interpretations (Cabello, 2017), which separates it from most other fields. Such is true of other areas too, such as General Relativity. Nowhere else in science would one refer to the "warping of spacetime" (Kersting and Steier, 2018; Woithe and Kersting, 2021) in regular language.

In fact, the unique "culture" is a core part of every scientific discipline, all of which are characterised by their own narratives. Such an interpretation forms the basis of the *Discipline-Culture* (DC) *framework* first introduced by Tseitlin and Galili (2005), which arose precisely from an examination of the nature of sciences as composed of seemingly distinct disciplinary fields, each with their own content, narratives, and languages. In the DC framework, scientific fields are organised into three components:

i. The *Nucleus*, in which are held the core, paradigmatic concepts which define the properties of the field
ii. The *Body* of working everyday applications of these principles
iii. The *Periphery* of alternative viewpoints and historical accounts.

Every scientific discipline is composed of elements of all three, and Physics as a whole is built up from a continuous dialogue of numerous interacting discipline-cultures, whose periphery shifts over time, resulting in an ever-changing landscape (**Figure 1**).

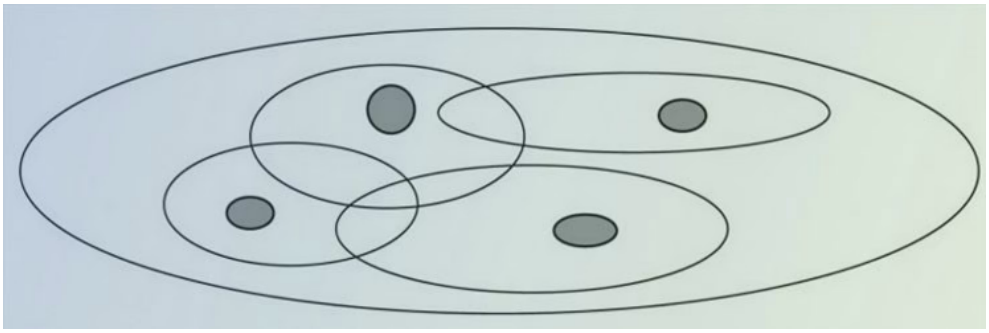


Figure 1. Physics as an interaction of several discipline-cultures (adapted from Tseitlin et al., 2005)

In Quantum Physics, the DC framework has been previously used by Weissman et al. (2018, 2022) to compare concepts included in formal education curricula. In the context of non-formal education, Goorney et al. (2022) proposed it as the backbone to a narrative approach, *culturo-scientific storytelling*, which takes participants on a journey through the DC, with benefits for engagement and the development of futures thinking skills (Levrini et al., 2019). In fact, we may consider the goal of non-formal education to be this introduction into the discipline-culture, resulting in students and citizens of the public getting familiarised with the language of the field, and thus not be prone to the hype and misinformation associated with misinterpretation of its culture via misuse of field specific language. In this research, we take community input to this end in the form of a survey around most important quantum concepts for public awareness, and use the DC framework as a lens through which to uncover the nuances of this discussion.

Methodology

In this work, we employed an iterative survey with open ended questions in earlier stages for exploratory purposes followed by grading in a later stage for rank ordering purposes. This process allows for expert input not only in the results of the study, but also in constituting the questions, ensuring they are representative. In the QT community, this method is also being utilised to identify the key topics for quantum mechanics in secondary schools (Krijtenburg-Lewerissa et al., 2019), and to create a competence framework and qualification profiles for the QT workforce (Gerke et al., 2020; 2022; Greinert et al., 2023).

Our study consisted of three rounds, each of which was disseminated to the QTEdu community of around 400 members through email newsletters and shared internally within the QuTE4E pilot. The preliminary round took place between September and November 2021 and involved 13 participants who filled out a Google forms document with open-ended questions. Based on the outcomes of the preliminary round, the first round of the survey was formulated using the SoSci Survey tool. **Figure 2** shows the timeline of the QuTE4E survey.

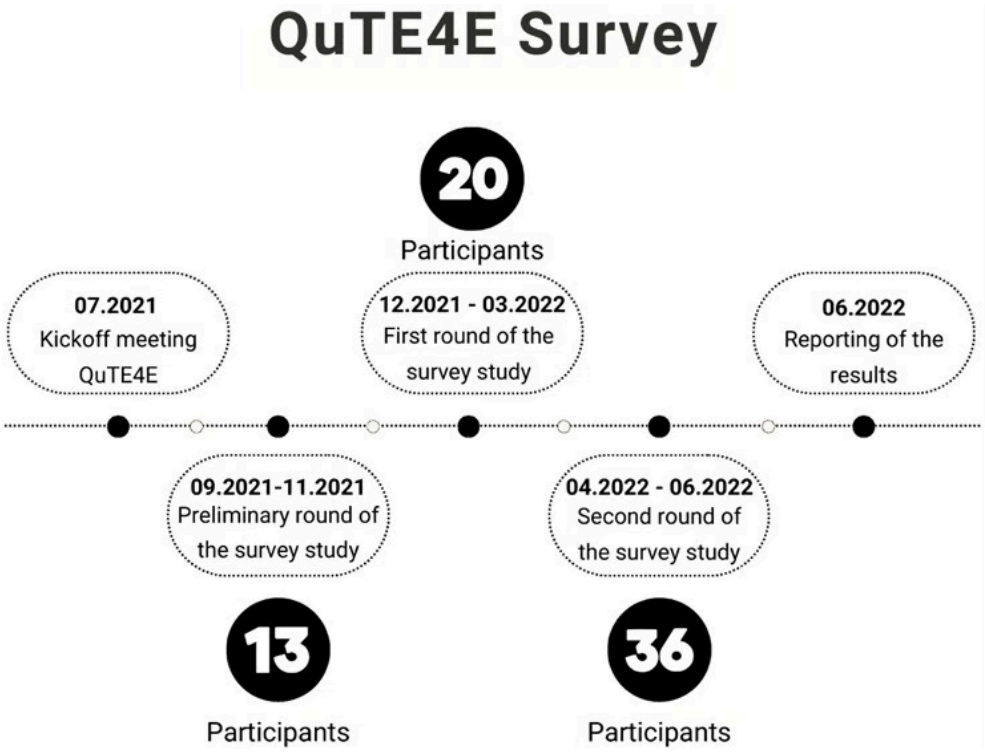


Figure 2. The timeline of the QuTE4E survey

The study underwent several small alterations between the different versions of the survey. **Table 1** illustrates the format of the question asked in the preliminary round and the final version. One example of such a change is the addition of the “Don’t know” option in the Likert scale, which was only included in the final round following a suggestion from a participant in the first round. Another difference between the first and second rounds was the inclusion of a “country” option in the background section of the survey for participants, which was only present in the final round. For the questions a five-point Likert scale was used ranging between the options “Not important at all” to “Very important,” with an added option of “Don’t know.” These modifications were made in an effort to continuously improve the survey and gather more comprehensive and accurate data.

Table 1. Comparison of preliminary and final round of questions

Preliminary round questions	**Second (final) round questions**
Which essential concepts of quantum physics should be utilized for outreach activities in quantum technologies?	Please rate the concepts/approaches provided below in terms of their usefulness to be utilized for outreach activities in quantum technologies.

The lists of items to be included on the questions were formulated in the following manner: initial lists of these items were created using the outputs of the preliminary round of the study, where experts were asked to put in their replies to open-ended questions. Following this, in the first round of the study the results of the preliminary round were presented to the participants

to be rated and additional items were allowed to be added by them. The items to be rated in the second round were then composed of those suggested in the preliminary round, along with those added in the first round. Through this, the iterative survey method allowed us to use community input not only in the results of the study, but also in constituting the questions. This helped to ensure that items chosen in the final round were representative, as they were provided by multiple experts (those completing the preliminary and first rounds), rather than only the researchers who created the survey, as would have been the conventional survey method.

Finally, there are three main points of limitations to be kept in mind when utilising the outcomes of this study. First, the study inputs and outputs were generated combining the discussions within the pilot project, and a survey study comprising three rounds of surveys with a total of 36 participants in the final round. Therefore, the findings presented here should not be taken as an exhaustive and complete representation of the community, but only a first step towards further understanding the intricacies of QT outreach. Second, as both the field of QT and the pressing needs of our world are rapidly changing and as the final round of this study took place between April and June 2022, the temporal limitation should always be noted. Finally, as the QuTE4E pilot project mainly consisted of researchers from the EU region, the outcomes are biased towards representing this region's perspectives.

Findings

In this section, we provide further details of the final survey and participants, present our findings and some comments of the participants obtained from the final round of the study. Most discussions on the findings are reserved for the Discussion section.

During the final round of the study, a total of 446 clicks were made to the survey and 36 participants completed it in full, which might be attributable to the length of the survey. Only the 36 participants (out of the 400 members) who completed the survey in full were taken into account in the end for our analysis, and we do not know which kind of experts answered beyond the data provided by them on country, type of positions, and years of experience in QT outreach efforts in the demographics section of the survey. These participants were geographically distributed as follows: 21 from the EU countries, four from Southeast Asia (India and Malaysia), seven from the UK and the USA, and four from other countries (Ethiopia, Tunisia, Turkey, and Zimbabwe).

In terms of their outreach positions, three categories were identified: academic, industry, and non-profit. Of the 36 participants, a total of seven selected one or more of these options, with only one participant (from Tunisia) selecting Outreach (non-profit) as their sole "position." The remaining six participants who had outreach responsibilities also held at least one other non-outreach position. In total, 10 out of 36 participants reported having multiple positions or responsibilities, with six of these participants having outreach responsibilities as well. It was also observed that PhD students who were involved in outreach efforts typically had at least one other responsibility as a researcher or administrative staff member.

In terms of experience in QT outreach and education, four out of the seven participants with outreach-related positions had 1-5 years of experience, one had *"Less than one year,"* one had *"5-10 years,"* and one had *"10-20 years."* In total, three of the participants had less than one year, 21 of the participants had 1-5 years, two participants had 5-10 years, four participants had 10-20 years, four participants had 20+ years of experience in QT outreach or education while two of the participants noted that they are not involved in QT outreach or education. A summary of this can be found in **Table 2**.

Table 2. Distribution of QT outreach and education experience of the participants

	Less than one year	**1-5 years of experience**	**5-10 years of experience**	**10-20 years of experience**	**20+ years of experience**
# of participants with outreach experience (34)	3	21	2	4	4
# of participants with outreach positions (7)	1	4	1	1	0

In the survey, we asked the participants to rate the concepts provided in terms of their usefulness to be utilised for outreach activities in QT. The results are rank-ordered in **Table 3**, where the highest ranked items are located at the top of **Table 3**, and the lowest ranked are at the bottom. In addition, the authors assigned each a position within the *discipline-culture* of quantum physics, based on the findings of Weissman et al., (2018 and 2022), discussed below in the *Discussion* section.

Table 3. Concepts to be utilised for QT outreach activities (rated in terms of their usefulness), and their position in the discipline-culture of quantum physics ("Not important at all" = 1, "Very important" = 5)

Concepts	**Grade**
Superposition **(Nucleus**)	4.72
Measurement (**Nucleus**)	4.69
Quantum state (**Nucleus**)	4.69
Qubit (**Body**)	4.58
Entanglement **(Nucleus**)	4.39
Interference (**Body**)	4.31
Technological concepts (like quantum computers) (**Body**)	4.22
Probability amplitude (**Nucleus**)	4.19
Quantum coherence/decoherence (**Body**)	4.06
Physical qubit platforms (atoms/ions, photonics, superconductors, etc.) (**Body**)	4.03
How the theory predicting only probability and uncertainty leads to technology of highest precision and control (**Periphery**)	4.00

Concepts that can be explained using binary logic and arithmetic (**Periphery**)	3.97
Algorithms (**Body**)	3.80
Classical computing (**Periphery**)	3.75
Tunneling **(Body**)	3.69
Quantum optics concepts (**Body**)	3.69
Spin (**Nucleus**)	3.67
Bell test (**Body**)	3.51
Quantization (**Nucleus**)	3.17
Complexity theory (**Periphery**)	3.03

The concepts of superposition, measurement, quantum state, qubit, and entanglement are top five. Meanwhile, more QM-heavy concepts such as spin, quantization, Bell test, tunnelling, quantum optics ranked rather low. Complexity theory, a CS-heavy concept, is also ranked the least useful concept.

Discussion

Before any consideration of implications arising from our results, we first highlight that the sample size of the study was limited. However, as we discuss here, the findings raise some interesting ideas which may still provide valuable insights for QT outreach practitioners, developers and decision-makers. One particularly notable outcome of the study was highlighting the ongoing tension within the community surrounding the perception of QT as a field primarily for physics and physicists versus a more interdisciplinary field in which computer science and other disciplines play a central role. This tension became evident in our community meetings for the reporting of the results of the study, as those (primarily) from quantum physics education and outreach backgrounds were questioning the results, for example not believing that spin as a concept could have been ranked so low. In comparison, those more focused on QT and quantum computing education and outreach argued against the utilisation of spin as a concept for outreach purposes, which led to fruitful discussions and our belief of the necessity of introducing the discipline-culture framework into QT outreach efforts. Furthermore, this tension has been observed in the literature on quantum computing since the early 2000s (Mermin, 2003), is particularly notable in the field of quantum computing, which has seen the emergence of computer science-oriented approaches to teaching (Yanofsky and Mannucci, 2008) and outreach and education activities (Salehi et al., 2022). In these approaches, quantum computing is often presented as a generalisation of probabilistic computing, a perspective popularised in Scott Aaronson's book "Quantum Computing Since Democritus" (2013). However, it should be noted that quantum computers are still in their early stages of development, and writing effective quantum algorithms often requires taking into account the specific physical hardware being used. This highlights the need for interdisciplinary collaboration and a balanced approach to QT outreach and education that takes into account the perspectives and expertise of multiple disciplines.

Concepts and Approaches

First, we note that the top three most important concepts rated for inclusion are: Superposition, Measurement, and the Quantum State. All of these are considered core concepts in the field and some of the defining characteristics of quantum systems, thus lying in the Nucleus of the DC. Indeed, they can be found in the Postulates of Quantum Mechanics (Sakurai, 2017). These ideas are some of the most fascinating that can be encountered in Physics, and have inspired works of art (Levrier, 1997), science fiction, and several generations of scientists. It is possible that the participants rated these highly for their role inspiring the public with interest in the field.

After the concepts in the Nucleus, the next most popular for inclusion are those in the Body, in particular Qubits, Technological concepts (like computing), and Interference. One explanation for this may be that both investment and public interest in Quantum Technologies is strongly skewed towards Computing over the other fields of Sensing and Communication (Mckinsey, 2022), resulting in Qubits and computing concepts being rated greater in value than others. Interference, on the other hand, is very often discussed alongside Superposition and Measurement, which may explain its inclusion among the most important concepts in the Body of the DC.

It is also interesting to see that aspects of the Periphery, such as Complexity Theory and Classical Computing, are generally rated with lower importance than those concepts in the Body and Nucleus. Previous work (Weissmann et al., 2018; Levrini et al., 2014) has identified historical and alternative viewpoints of the field to hold great value in promoting skills such as scientific thought and future-awareness. However, study participants may have considered these benefits to be less impactful than the “wow factor” associated with some of the Nuclear concepts. On balance, given the limited time and resources available, this may explain the relatively low importance given to the concepts in the Periphery of the DC.

Finally, given the debate between whether QT lies within the domain of Physics, Computer Science, or elsewhere, it is interesting to consider whether quantum physics or quantum information science (QIS) is the relevant DC to take into account for QT. The Qubit can be considered as a core Nuclear concept for QIS while it is a concept located in the Body of quantum physics. In the discussions and comments collected during the study, we noted that the discourse around QT was strongly dominated by physics and physicists, a finding consistent with previous bibliometric studies (Seskir and Aydinoglu, 2021). However, the idea that QT builds largely on other fields was also highlighted in some responses, suggesting that this debate is far from being resolved.

> Participant: “Globally, this study seems to assume quantum technologies is only a problem of physics and/or physicists. A quite large part of the work involves computer scientists (algorithmics, quantum software, language) and there are already problems in communicating this towards the physics community. This difficulty of communication goes both ways.”

One particular point of discussion within the pilot on our findings regarded the concept of Spin. Spin was ranked rather low in terms of usefulness for QT outreach activities, which surprised some of the outreach and education practitioners in the project. However, outreach practitioners, particularly those working in the field of quantum computing and programming, identified the difficulty of effectively utilising the concept in an outreach context. The way that Spin is typically communicated to a non-expert audience through the use of analogies such as a spinning ball can be confusing and misleading, as Spin is not a physical property in the same way that an object spinning on an axis is. Additionally, much of the practical value of introducing the concept is in introducing Qubits and thus applications such as quantum algorithms. However, these can still be understood without the concept of Spin, and thus on balance it may be better to avoid the concept in outreach settings, for risk of miscommunication and better use of limited time.

The final insight we would like to highlight from this study is that QT outreach should be diversified to meet the needs of different target audiences with respect to different target goals, as it is not a field emanating from a single discipline, but in fact has several divergent background disciplines that it is built upon. A recurrent theme that emerged during our conversations within the pilot and is clear from the resulting concepts in the study, was whether communicating quantum mechanics is a necessity to effectively communicate QT to non-expert audiences. On one hand, there is a push to make quantum theory understandable as the enigmatic source of QT (Vermaas, 2017), on the other hand, there is an added benefit of considering each QT and their applications by being specific (Coenen, et al., 2022). This suggests that the appropriate role and use of quantum mechanics and theory in QT outreach and education is a topic that deserves further attention and discussion within the community.

Conclusion

In this study we presented a portion of the findings of a survey study that was conducted as part of the QuTE4E pilot under the QTEdu CSA of the European Quantum Flagship program titled “Quantum Outreach: Stakeholders, Opportunities, Problems, and Solutions”, and an analysis of the findings related to the rank-ordering of the concepts for their utility in QT outreach activities through the *discipline-culture* framework. The primary finding of our study is that QT outreach and QM outreach, although having much in common, diverge in their relation to certain concepts (such as qubit and spin). This hints that as QT becomes more of a normalised and widespread set of technologies in the public domain and democratised (Seskir et al., 2023), further diversification of outreach methods moving away from QM outreach methods particularly relating to non-physicist audiences are needed.

This study is foundational in the new approach the QuTE4E pilot calls *Physics Outreach Research.* We believe that outreach, as non-formal education, requires the same degree of research-based attention and evaluation as classroom STEM teaching has had for decades. Our results are a first step in this important direction, unveiling several tensions in the community. It is natural then that while these debates continue, there can be no single best approach for which concepts to include in QT outreach activities. However, we encourage

educators to reflect on the purpose for which they are communicating QT. In doing so, they may uncover the most effective approaches for their own needs, selectively incorporating concepts from the Nucleus, Body, and Periphery of QT. This research may provide valuable insights and guidance for individuals and organisations engaged in quantum outreach efforts, as well as those interested in learning more about this rapidly-evolving field.

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Article 1.8: Why Teach Quantum In Your Own Time: The Values of Grassroots Organizations Involved in Quantum Technologies Education and Outreach[115]

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This paper examines the intersection of goals and values within grassroots organizations operating in the realm of quantum technologies (QT) education. It delineates a fundamental distinction between the objective to provide education and the drive to democratize learning through principles of inclusivity, accessibility, and diversity. The analysis reveals how these organizations navigate their nascent stages, grappling with the dual challenge of adhering to their foundational values while aspiring for sustainable growth and development in the highly specialized field of QT. The study uncovers the strategic approaches adopted by these entities, including efforts to create educational ecosystems and foster community engagement. The research underscores the potential vulnerabilities of these grassroots organizations, particularly in relation to the longevity and evolution of their initiatives as members transition into professional roles within the quantum sector. Through this investigation, the paper contributes to a nuanced understanding of how emerging educational organizations in the QT field balance their ideological commitments with practical growth considerations, highlighting the critical factors that influence their trajectory and impact.

Keywords: Quantum Technologies, Quantum Education, Grassroots Organizations, Workforce Development, Quantum Ecosystem, Quantum Divide, Democratization, Inclusivity, Diversity

Introduction and Background

Quantum education is one critical pillar, enabling societies to make the most use of second-generation QT, by training future workforce and equipping the society to comprehend and trust in this emerging technology. Quantum education is on the one hand about providing educational programs at high-level institutions, designing curricula, and training future physicists, engineers, and quantum information scientists about exploiting quantum phenomena. On the other hand, it is about creating a broad understanding of the capabilities of QT, enabling discourses, and open innovation besides societal engagement and allowing for participation, gaining a broad quantum readiness of the future workforce and in society in general [1, 2]. QT is

[115] https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-025-00345-2

expected to impact society at large. Even though it does not seem clear yet, in which depth and significance this impact will be, it has been becoming apparent that QT has the potential to change the current status quo of information security and internet communication and even further there is potential for the disruption of well-established concepts as we know them [3, 4]. Over the last couple of years there has been an increasing call from researchers towards responsible innovation, participation, and engagement of the public sphere, so that the discourse of the chances and impacts of the emerging technology will be open, diverse, and enriched by various perspectives [1, 4–6]. The manifesto by Coenen et al. argues for QT to be comprehensible to different groups of stakeholders, specific, open, accessible, and responsible, considering also unforeseen or unintended consequences [2].

On the other side, there is an ongoing quantum race, where companies and countries vie for technological and competitive advantage [4, 7], having national strategies and programs in place [8]. There has been a steep increase of newly founded start-ups, patent applications and high investments in QT in recent years [9–11], contributing to a culture of competition and rivalry about intellectual property rights and trade secrets [4]. There are an increasing number of news about export restrictions of essential parts of quantum computers for reasons of national security [12–14]. According to Kop et al. this rivalry can be a driver for innovation but may be a hindrance to ethical development, as ethical, legal or social implications (ELSI) are not incentivized [4]. Additionally, this trend has a strong effect on the disparity, inequitable access to QT and essential resources, it worsens the so-called quantum divide [15], a concept that refers to a significant gap in access and utilization of QT causing inequality. A study by Gercek and Seskir provides a detailed image of a quantum divide in science, in technology, between countries, and between societies [16]. Due to that mentality of ‘the winner takes it all’ there are different approaches to creating QT in different regions and some countries have nor the resources nor access at all to existing technological approaches, tools, and knowledge, increasing a gap between the ‘haves’ and ‘have nots’ even further [15]. That different perspectives could be a great game changer for the development of QT is an ongoing discussion in literature, with the ideas of knowledge being exchanged more freely between countries of similar values and synergies of different approaches, methods and tools being used effectively. Scientists are talking about bridging the quantum divide [3, 4, 15], emphasizing the advantages of participation and engagement of diverse perspectives in the innovation process to fully understand, utilize, and benefit from QT [4, 15, 16]. Some argue that a diverse and inclusive responsible innovation of QT facilitates an effective and sustainable development, actually developing and using the technology for real-world purposes on a larger scale [4]. Additionally, democratic engagement would create broad access to this emerging technology, building up a comprehensive knowledge base, reducing hesitancy and increase awareness, which would support entire ecosystems and market formation efforts [5]. Another benefit, scientists argue for, is that societies would be a lot stronger in facing risks of dual or malicious uses of quantum applications, that could harm societies on another level risking a destabilization and undermining trust in institutions [17].

The inclusion of quantum grassroots organizations, that are a form of upstream engagement of the public and are an integral part of civil society organizations [5, 18], into national quantum strategies and policy makings finds so far only little attention [18]. But, there is a strong focus on building up educational programs. Scientists, the industry and governments are addressing a

shortage of quantum literate talents, pushing to build human capital in quantum. Over the last ten years, many education initiatives have evolved in the USA, Canada, Europe, India, Singapore, Japan, South Korea, Australia, South Africa, and many more [19]. These educational programs focus mainly on quantum physics, quantum engineering, and quantum information science targeting STEM students and are mostly run by well-known universities. But studies show that they lack a gender balance and an inclusion of people of color and minorities, as well as low-income students [1, 20–22]. Despite a well-known workforce shortage and calls from ethicists about a need for diversity and inclusion in the quantum sphere, the progress seems slow. According to Wolbring, academic literature concerned about QT rarely to not at all addresses topics that relate to social implications as well as equity, diversity, and, inclusion [23].

Kaur et al. have analyzed different pathways that facilitate quantum education, showing that next to academic degree programs, there are also shorter trainings that are fitted to the demands of the job and real-world projects [19]. Further initiatives with a focus on diversity and inclusion are established, for example, online degrees, to be accessible to more students. The European Quantum Flagship program, a research and innovation initiative by the European Commission, has started DigiQ, a virtual education program in addition to any master's degree [24]. Furthermore, the Quantum Flagship is monitoring the progress of QT and has dedicated one scorecard entirely to education, evaluating outreach, the offered training modules, adoption as well as diversity and equity. The numbers reflect a significant increase in educational efforts over the past two years, with ambitious goals set for 2030 [25]. While academic programs are crucial for building a quantum-ready workforce and are in high demand for quantum industry job profiles [26], it's important to recognize the need for more diverse efforts. These include attracting quantum enthusiasts, offering learning programs beyond university through experience, learning quantum skills through training courses, and contributing to quantum communities [19].

Research question

Quantum grassroots organizations create global and local quantum communities, contribute to quantum education, and gain more quantum enthusiasts. Over the last decade the organizations have become part of the quantum ecosystem being in the position to support a quantum literate workforce and science communication to a larger audience. This study 'Why teach quantum on your own time' raises the question of why people voluntarily contribute to quantum education: Do they align with current debates regarding the workforce gap, quantum divide, and calls for responsible innovation? Are they pushing towards societal change by popularizing quantum education or are they rather eager learners supporting each other? With the study, we want to capture their reflection on their goals (what do they aim for?), values (what motivates them?) and teaching and learning methods employed (how do they do it?), providing a comprehensive understanding of their contribution to quantum education and quantum ecosystems.

In this regard, we employed a survey and conducted semi-structured interviews (more on these in the Methodology section). Our main questions in the survey and interviews were:

(1) “What is the main goal of your organization? Could you please provide us with some more information about the intention of the organization?”

(2) “What are the most important values of your organization? Please list at most 5 values your organization works with. Please order the values you just named from highest to lowest.”

(3) “What are the teaching/learning methods that your organization employs?”

In the following section, we introduce the methodology of the mixed-methods approach, providing an overview of the study's concluded design, how the data was evaluated, and showing the limitation to the study. Afterwards, the results section mirrors our three main questions and is enriched by findings in the organizational set-up and demographics. Moreover, comparing goals and values between regions, we found some trends of local characteristics, which are described at the end of the results. Finally, there is a discussion section that aligns the results with current findings in research and is followed by a conclusion of the study.

Methodology

Research Design

Through the use of mixed methods, this study employed a survey and interviews with quantum grassroots organizations. The research focused on organizations characterized by volunteer participation, bottom-up structure, non-profit orientation, and dedication to quantum education and/or outreach. The selection of these organizations was carefully conducted through extensive searches on LinkedIn and Google building upon previous projects, one on mapping the Communities of QT [19] and another one that ran as a summer project in 2023 with volunteering interns, called QInterns, under the QWorld’s 2023 summer internship program. A list was generated of existing grassroots organizations to which the survey was distributed. The survey included 13 questions in total that addressed demographics, personal membership, motivation, and organizational goals in the first section, whereas the second section contained the organization's perceived five core values, which participants were asked to rank, teaching and learning methods, and outlook. The interviews were primarily with the organizations' founders and established members, and the questions were congruent with the survey, aiming at a better understanding of the survey responses. The interviews were conducted in two rounds. The first round of interviews was aimed at organizations that were globally active and well-established as grassroots organizations. The second round of interviews focused on the geographical location of grassroots organizations to gain a better understanding of regional differences. Three organizations were identified as focus groups and observed in more detail, aiming at a better understanding of congruity of their named values. They were selected based on their global set-up.

Data Collection

The survey, which was designed using Qualtrics software, was distributed to 66 grassroots organizations around the globe, to which 18 organizations participated via the survey, of which only 15 responded to all questions. There were 20 interviews with participants from 17 organizations chosen out of the 66 due to their size, location, and availability for interviews during the interview phase in November 2023. From the two big players, QWorld, with their 32 local spin-offs called QCousins, and OneQuantum, with 12[116] communities worldwide, there have been three local organizations of both chosen. The remaining 11 organizations in the interview set act either purely global, without local spin-offs or only locally, focusing on their region or state. Out of all the organizations interviewed, three global organizations were interviewed twice, addressing two different long-term members or a member and a founder. Overall, there were 22 organizations participating by survey and interview. The grassroots organizations were from Africa (6), Asia (5), Europe (3), North America (7), and South America (1). Participants were invited to partake in a 60-minute interview via Zoom, and each session was recorded and transcribed using AI f4x transcription software.

Evaluation

The survey data was analyzed using Excel and SPSS, while the transcripts were carefully evaluated with the assistance of MAXQDA. The interview responses were analyzed with codes based on the participants' statements. To further refine the responses, sub-codes were created from the main codes. These categories were then linked to the survey responses to provide a comprehensive and detailed analysis. Standardizing the spelling of all terms ensured consistency throughout the analysis.

Demographics: The data on organizational structure and demographics was evaluated from the survey and the interviews and also compared between the statements of different members of an organization, where available. Where statements diverged, the mean value was calculated. The questionnaire did not contain a specific question on the year of foundation of the organizations, but the data was available in 12 interviews. Missing information on the founding year was researched on the Internet via the organizations' websites and LinkedIn, whereby the founding year was researched for all 66 grassroots organizations and presented as a supplement. The list of all grassroots organizations was extended again in 2024 and 3 additional grassroots organizations were found. Of the 69 organizations, the year of foundation could not be determined for 3 organizations.

Goals: The objectives mentioned were summarized according to the most frequent determining factors of all mentions. Since grassroots organizations mentioned between 3 and 5 goals in free text, it was possible to assign multiple mentions to an organization. In the survey, only 12 out of 15 organizations responded to the question about goals, so together with the interviews, a total of 20 organizations responded. First, the goals in the survey data were summarized according to

[116] According to the OneQuantum website, there are 22 chapters, but only 12 could be identified during the study.

the most frequently cited determinants. Then, the interview data on goals were assigned to codes already derived from the survey mentions. Codes were expanded from all interview data. Goal scores from both data sources were compared and adjusted to achieve standardization. Once the final scores were established, the two data sources were compared again. A data set for quantum education allowed for a more detailed breakdown of different educational goals due to the data available. This is shown in Figure 3 in the results section.

Values: The data on values was counted by frequency in both the survey and interviews but also evaluated by ranking, showing the frequency count of the highest value. Some survey participants mentioned value pairs like 'openness & accessibility' which was counted as two separate entries, counting 28 entries from 22 organizations.

Teaching and learning methods: The data on teaching and learning methods were summarized based on the most frequently mentioned factors by participants in both the survey and interviews.

Results

Organisational Structure and Demographics

Data on size was available from 21 organizations. 25% of them (5) have less than 10 people, and almost 60% (12) have a core of 10 to 20 people. Less than 20% (4) have more than 20 people. A vast majority of the people working within these entities are volunteers participating in university or school and define its stability as they transition into various parts of their career.

The interviews provided insight into their organizational structure: There are global organizations that work and act globally and/or set up local divisions, connecting through digital platforms like Slack or Discord. On the other side, there are local organizations that act in their country or a region of the country and do not belong to a global network. Most of the organizations interviewed showed signs of professionalizing their work structure with different departments and working groups, with strategic planning, task orientation, and regular meetings. The following statements show their professionalizing efforts:

> *"In our team we do quarterly meetings where we […] think about, what are our goals for this next three months? What can we measure those by? […] the way that our meetings typically go is: I [founder of the organization] will start by giving my overview on how the quarter has gone. I'll celebrate our successes. I'll talk about some things we could have done better and just talk about our general mission and reminding people of what that is, and then I'll open it up to everyone. We have like a whiteboard sticky note session where everyone can talk about what they think is really important to get to this quarter."* (Participant 13)

> *"Those 30 people that work on the content, they're divided into five teams. […] we have people specifically for planning, webinars and recording interviews. We have people specifically for creating the marketing content that we use on Instagram, high level management and organization of that. Also, directing educational program development by doing internal and external outreach."* (Participant 3)

But not all organizations were in such thriving conditions. Grassroots organizations depend mainly on volunteers, facing a steady in- and outflow of members when degrees are finished and careers are pursued, leading to transitions of founders and key figures in the organization.

> Participant 20 reported that the organization *"is in hibernation at the moment, so we have not organized any collective events for more than a year. It's mainly because me and my co-founder have moved, so we had our own problems moving to other countries and settling down".*

Overall, the interviews showed little evidence of transition structures for members in key positions.

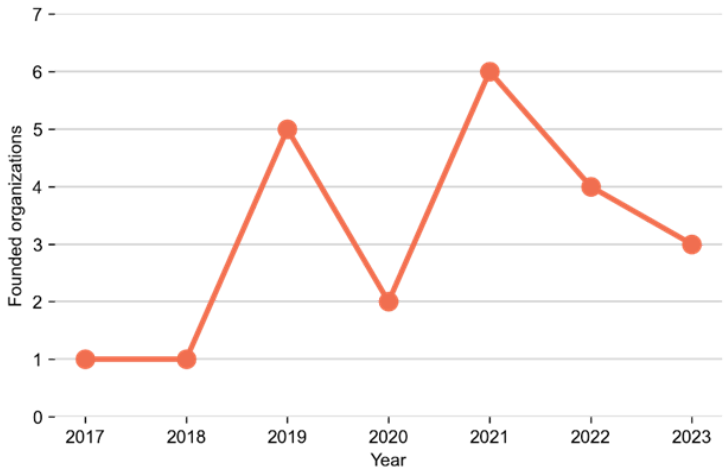


Figure 1: Number of founded grassroots organizations per year (participants of the study).

Looking at the age of grassroots organizations, they are mainly quite young. Most of the organizations were founded in and after 2019 and 2020, which can be explained by the creation of global parent organizations around 2019 and the creation their local spin-offs around the world. The two largest global organizations, QWorld and OneQuantum, both founded in 2019, have since created about 44 local spin-offs. Both graphs, Figure 1 and Figure 2, show a very similar curve pattern, comparing the number of study participants and all identified grassroots organizations, with a peak in 2021.

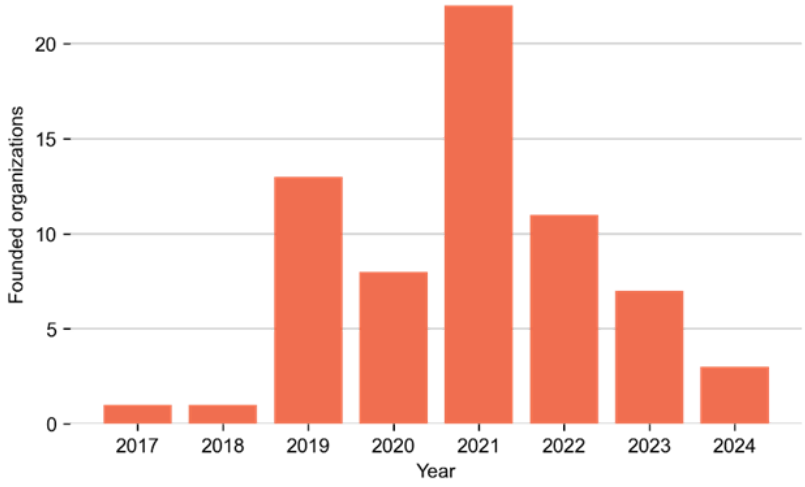


Figure 2: Number of grassroots organizations founded per year from the full list of 69 grassroots organizations, minus 3 organizations without data for the year of founding.

The growth of new organizations coincides with several factors. First of all, some organizations report that they became interested alongside with the hype around quantum computing, for example, when Google announced that it had achieved quantum advantage in 2019. [27] Another prominent attraction factor seemed to be the global pandemic of COVID-19, which pushed education massively into online spaces, and personal periods of isolation and/or quarantine led to an increased use of online communication and social networks [28]. IBM for example offered their Qiskit Global Summer School in a virtual open-access space, reaching over 4,000 participants [29]. The following statement indicates that the IBM initiative was a critical factor in the creation of the organization.

> *"We, I and a bunch of other students learning quantum or involved in Quantum met at the first global summer school in 2020. We all met at the Discord server that they had and eventually we all got to talking about creating communities and creating spaces for learning more about quantum effectively and in a way that is open source and inclusive and eventually so on and so forth. We just created the space with all these resources online. And it's not just us, but we also invite everyone in the community and everyone online to participate as well and come in and join and contribute to resources and contribute to learning together."* (Participant 6)

Goals

In the field of quantum science and technology, grassroots organizations have emerged as influential facilitators in education as well as creating opportunities for learners, both being the most frequent mentioned goals. Figure 2 shows the full distribution of mentioned goals.

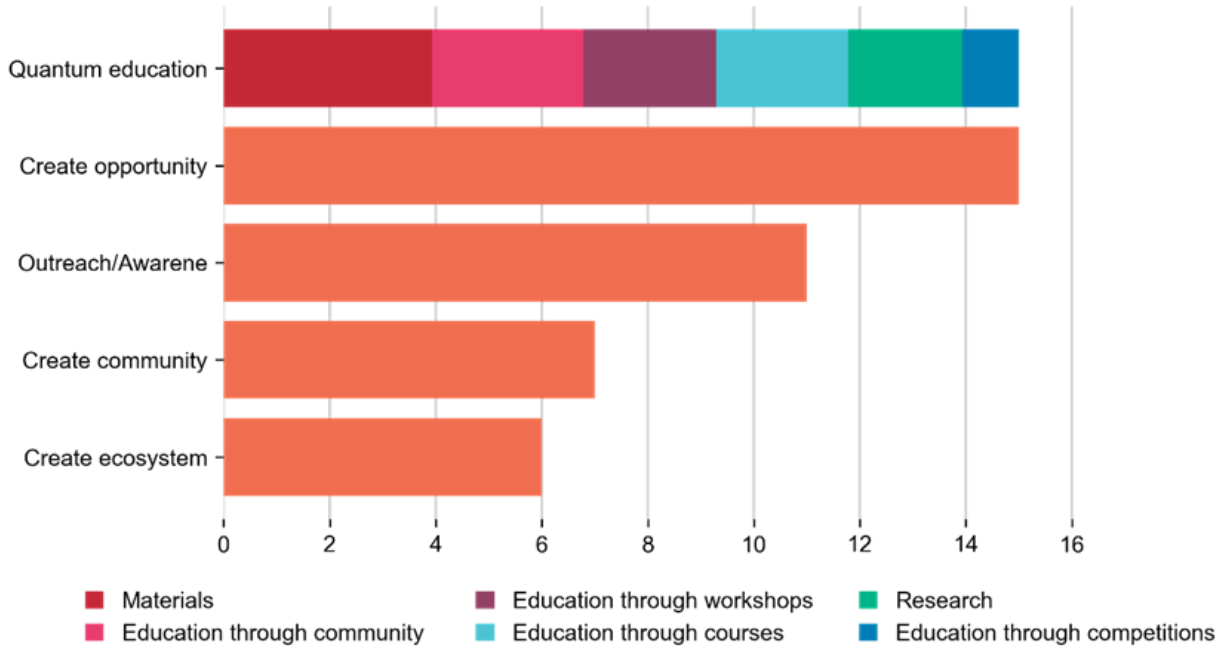


Figure 3: Goals of grassroots organizations (N=20), sorted after frequency and grouped according to similarities. The goal quantum education was broken down into sub-goals due to data availability, showing their focus on different educational styles.

Our research has found that grassroots organizations demonstrate a strong commitment to **quantum education** and to the development and provision of accessible and comprehensive educational materials, supporting learners across a range of educational stages. The organizations offer diverse educational possibilities, addressing different learning styles: theoretical to practical, social to independent, and competitive to collaborative learning, which will be addressed further down, when talking about teaching and learning methods. Based on the different methods in education the graph on quantum education was already split, showing the different results of educational styles. It shows that the distribution of mentions is quite similar, offering a diverse range of learning about quantum. Most of the grassroots organizations (n=15) are dedicated to quantum education and aim to reach STEM and non-STEM students at all levels, academics, professionals, and the general public. They aim to support the quantum journey for all learners, guiding them along the way and nurturing talent from an early age.

Another goal mentioned as often as education was **creating opportunities**, which is an aggregation for mentoring and supporting students, providing ample opportunities to learn, and building a successful career in quantum. By emphasizing this goal, grassroots address various needs in quantum. By creating access to resources and supporting students in their learning, they contribute to democratize learning. Additionally, they aim at fostering talent from different backgrounds, addressing diversity gaps in quantum education and aiming at people to learn about quantum to eventually contribute to a skilled workforce and create impact. Over half of the surveyed organizations are concerned about the lack of diversity in the quantum workforce. Studies reveal that STEM graduates from educationally marginalized groups are

underrepresented in terms of race, ethnicity, sexual orientation, and gender [20, 22]. A study from 2024, that is mainly concerned with quantum information science (QIS) in the USA, showed that QIS education programs are less available in rural states and at institutions that serve more low-income population in the USA [21]. Grassroots efforts aim to create opportunities for minorities such as women, people of color, and other minor backgrounds and actively placing them in niche areas of science such as QT. They create a supportive and safe environment and target underrepresented people. The inclusivity objective is an important contribution to democratizing access to QT [5, 21, 30], not only in terms of fair educational opportunities but also providing chances for societies that are less technologically advanced and are not as equipped with the resources to take advantage of the potential benefits that QT can offer [4, 15, 31]. Organizations from disadvantaged regions and the Global South, particularly low-income countries in the southern hemisphere [32], address inclusivity as part of global quantum development at a systemic governance level, meaning that these organizations aim at creating opportunities for their society on a global scale.

> "*IBM experience is not accessible in some African countries. […] We don't have a quantum computer in Africa yet. So, how can we mitigate this to make sure that at least the interested people have the opportunity to learn? We try to create equality, whereby, we don't have the same resources as everyone else, but we do want to learn. We do want to also be part of this quantum revolution."* (Participant 9)

Outreach and awareness raising are inclining to attract members, media attention, and funding. Over half of interviewed and surveyed organizations named outreach as a goal to gain visibility, opportunities in partnerships and sponsoring and "*raise awareness about this emerging field of technology*" (Participant 17) within society as one participant commented or to "*increase the number of students who are engaging with this exciting field*" (Participant 15) like another participant responded. There was no particular group of grassroots organizations that declared outreach as a goal, but it can be said, that all grassroots organizations are concerned with outreach and awareness, even if they do not state it as their main goal.

Some organizations aim for a strong quantum **community** as a place to support each other on the individual quantum journey ("learning together"), to collaborate and connect with like-minded people, and to inspire members. Organizations that focus primarily on building a quantum community organize goals such as quantum education and opportunity creation in different ways. Learning becomes more of a social event, with less material and more focus on community facilitation, getting to know each person's context, and building community exchange. Because of this setup, they provide a platform for new members to join and contribute content, as well as get questions answered by the crowd. Their communities also strive to create a diverse, safe, and inclusive network.

> [We want] *"to support underrepresented groups, to keep them in quantum and to give them a network of people like them."* (Participant 18)

The goal **creating an ecosystem**, which was highlighted by six organizations, was often but not exclusively used by organizations from geographical regions that do not yet have a strong

presence on QT. Some organizations from the Global South aim to create an ecosystem and make an impact even before providing quantum education to youth or building a community. Being faced with the challenge that key stakeholders such as academic and governmental institutions and the business community are not fully aware of the possibilities of QT, the goal of grassroots organizations shifts towards governmental, academic, business, and societal awareness.

Talking with founders of grassroots organizations (n=7) about their motivation shows the fine line between the goals of the organization and the values behind the organization. The founders had their own reasons for starting an organization in quantum education. One reported, that there was a lack of structured content for early beginners, another founder did focus on creating a community for learning together. One founder from Africa said, "*If you want to master something, you need to teach it*." (Participant 17), showing that this motivation was based on personal intend to deepen the understanding of the field and take on some form of leadership. Whereas these motivations were rather personal, another founder replied on a more structural level by explaining that the rapid pace of technological development in quantum is not being adequately addressed in education, leaving people behind.

> "*I use a train metaphor. So now this train is starting to move [...] Let's try to invite these people and they can catch this too. [...] If people are the first passengers, then everything will be much easier, because the later train will be very fast. You cannot catch it."* (Participant 1)

The statement also refers to the possibility of widening pre-existing divides in QT [15] and that the fair distribution of opportunities plays a crucial role in quantum literacy [4].

Values

The interviews and survey reveal a clear emphasis on inclusivity, accessibility, and diversity as key values for grassroots movements in quantum. People from diverse backgrounds and experiences unanimously emphasize the importance of creating an environment that actively welcomes everyone. The results mark a contrast between the goals and values of the organizations: While one of their main operational goals focuses on providing educational content, their core value system doesn't prioritize learning itself; rather, their values center on democratizing access to knowledge, appealing to diverse populations, and fostering inclusiveness across different backgrounds.

Of all the values mentioned, inclusiveness and accessibility were mentioned most often, followed by diversity, community, and collaboration, see Figure 5. Education and learning were mentioned 6 and 7 times, respectively. In contrast, if we look at the ranking of the highest values, learning and education are not mentioned at all, see Figure 4, instead accessibility is mentioned most often as the highest value.

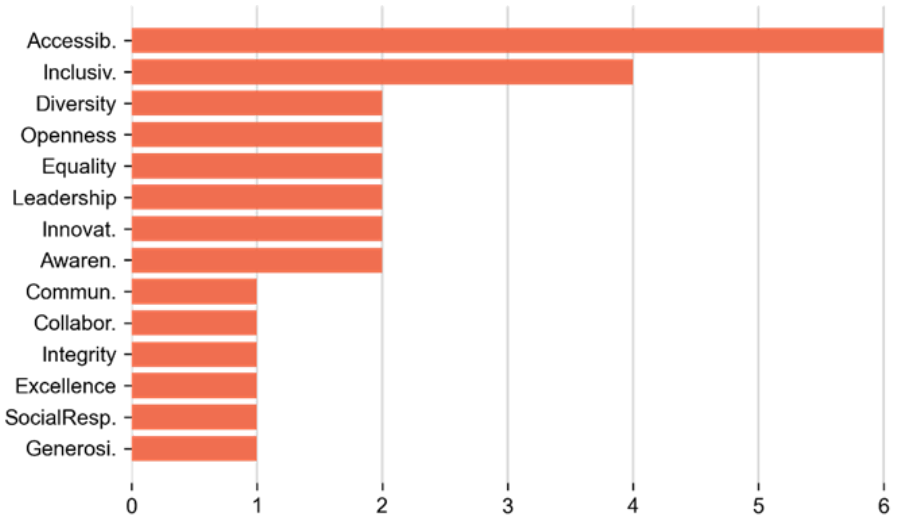


Figure 4: ranked values, frequency count of the highest value stated.

By prioritizing **accessibility**, grassroots organizations aim to break down barriers, ensure fair access to opportunities and learning materials, and foster a collaborative quantum community. They contribute to democratize quantum education by making quantum knowledge and resources available to everyone, regardless of background or experience. The term accessibility includes being open to all skill levels, to people with little financial resources, and being understandable, like easy explanations for starters, as well as covering many different mother tongues. Additionally, there is the accessibility to quantum computers, simulators, and research institutions that are country- or company-specific. This recognition of accessibility as a core value highlights the crucial role it plays in shaping the culture of these initiatives, making quantum research and engagement more equal and accessible to all and putting their efforts into bridging quantum divides. A quote from a global organization reflects that:

> *"We wish to foster the value of learning together through a community driven effort. And we want it all to be open source, not just in terms of like transparency, but also in terms of accessibility and inclusivity. So, we want as much about quantum computing that is accessible online to be available to people for free and available easily without barriers, be it economic barriers or other barriers, and prevent sort of restricted learning. We want to create more opportunities for people to learn the way they wish to learn about this field and eventually contribute to a skilled workforce."* (Participant 6)

Accessibility emerged as a value cited across all regions encompassed in the study (see Figure 5), underscoring its significance within the global community. However, it should be noted that while regional categorization provides a preliminary indicator of value distribution, the study design was not optimized for comprehensive regional comparison analysis.

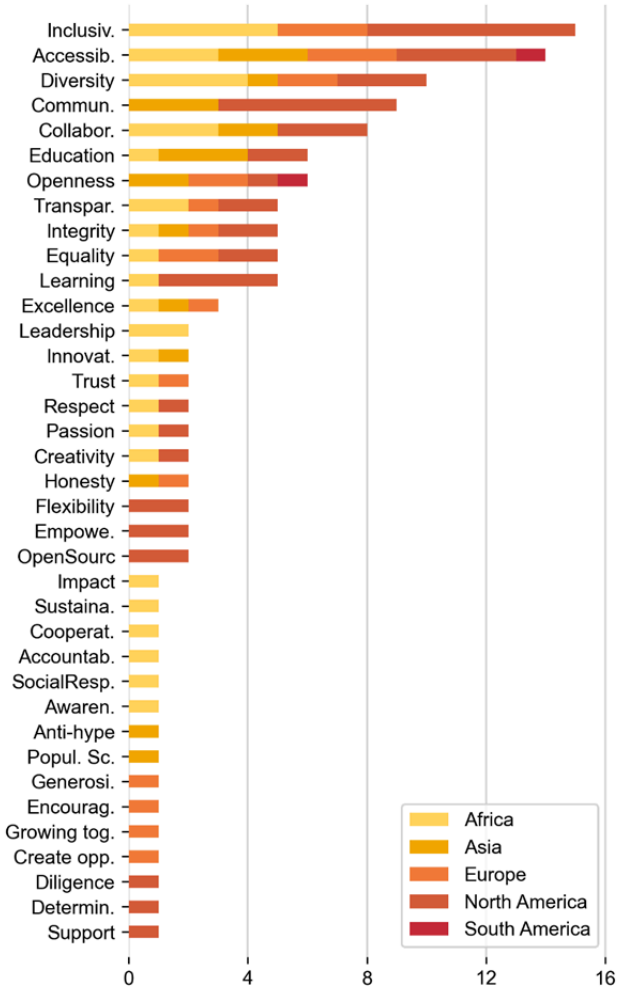


Figure 5: Frequency count of stated values per region, without ranking.

Inclusivity and diversity, being also positioned at the top among all mentions, are often-discussed values in the literature on quantum innovation, societal impact and workforce literacy [1, 33]. Recognizing inclusiveness and diversity as key principles underscores these organizations' commitment to leveraging different skills, cultural perspectives, and demographics for collective strength and overall benefit. Notably, both values demonstrated minimal representation in Asian and South American contexts; however, this observation must be interpreted with caution due to the limited statistical power resulting from insufficient data sampling density across these geographical regions.

The quantum grassroots talking points are best put in quotes:

> *"Inclusivity is a really big value for us, because we have people from many different parts of the world who have different backgrounds, different experiences and different exposures or different levels of engagement in their communities."* (Participant 2)

> *“Some values that we mainly prioritize would be, of course, one being diversity. It’s kind of implied there. But we do want to see more women and minority individuals enter the playing field. That is a number one goal.”* (Participant 14)

On a more structural level is this quote:

> *“The reality is that the STEM workforce still struggles with the diversity and inclusivity issue. [...] we want to really make sure that we are addressing the mistakes that were made when classical computers were being developed and make sure that from the beginning of the quantum computing revolution that we're making sure that education and that the field at large is inclusive and diverse. And so, we have a big focus on making sure that we're reaching people of color, those from rural or low-income communities, women, and non-binary students, and not just make sure that we're reaching them, but that they feel empowered and included to like and feel like they belong in this space.”* (Participant 15)

The research findings reveal that **community engagement** and **collaboration** emerge as important values, as they were mentioned by over half of interviewed organizations, which create (virtual) places to go to, a community, a knowledge exchange, and a network where people can find resources, answers, and a support network. The intentions behind building a community are manifold, it is about “*fostering a sense of learning together*” (Participant 6) or to “*unite with other like-minded people*” (Participant 20) and creating spaces that empower people to realize new ideas and projects. It is also a place of being motivated, inspired by others. Collaboration is not only seen as an internal value, collaborating with others, it is also about collaborating with partners, like in academia, arts, or governmental organizations and is closely related to the goal creating an ecosystem.

While **leadership** values may not be a priority for most organizations, the research identified a subset of organizations that place a high value on leadership. These organizations are driven by a collective ambition to make a meaningful contribution to the advancement of quantum science and technologies. Notably, leadership values play a crucial role in organizations operating in countries with limited quantum-specific resources, national programs, funding, educational programs, and accessibility to the latest QT.

The overall organization's value set addresses the need for a diverse quantum-literate workforce, attracting people without a STEM background and contributing to diversifying the quantum workforce overall. Moreover, this intense focus on inclusivity, accessibility, and diversity aligns with a broader societal goal of fostering innovation and progress in QT. As these organizations work to diversify the quantum workforce, they are also seeking to create a cultural shift that prioritizes fairness and equality to drive progress in quantum research and development.

Teaching and Learning Methods

Grassroots quantum organizations offer various learning materials in different forms to their community, most prevalently through books, videos, webinars, lectures, explanatory apps, and

forums. Not only do they provide guidance and basic introductions for complete beginners, but also advanced trainings and activities for more experienced people. They offer classic lecture-style training to provide the groundwork for QT basics and theory, guided introductions, and presentations of different quantum topics, mostly related to quantum computing, to guide the learning journey and support self-learning. The depth and quality of this material can be considered as widely diverse, depending on their resources, focus or goal, strive for excellence as well as their support through collaborations and within their network. For example, an organization that focuses exclusively on providing content to learners and doing summer programs and courses have a higher dedication to creating learning resources than community-oriented organizations that use community efforts to create content and events for learners. Also, considering the average size of the quantum grassroots organizations, it strongly depends on their available capacities. But grassroots organizations are quite creative in finding different pathways: Some, rather community oriented grassroots organizations use journal clubs, offering a collection of the latest research and news articles that can be discussed within the community. They use the wisdom of their community to support academic members and PhD students who are part of the community in their respective research efforts and share knowledge openly within their organization. Since most members of global grassroots organizations are located worldwide, members in the quantum grassroots community can gain insights into quantum research from around the globe, which is mutually beneficial for academics, PhD students, and other members.

> *“We also do a journal club which is essentially taking a research paper somewhere online and breaking it down to sort of help others understand, but also encouraging them to read it up first and then sort of having a session where everyone comes in and asks questions about it and has like a roundtable discussion. […] However, we try to make it as easy as possible so that anyone can join in.”* (Participant 6)

Grassroots organizations focus on collaborative learning by creating events like hackathons and learning camps to establish a network and learning environment with others and community-based forums for open discussions or curated Q&A sessions. Through events, grassroots organizations attract new members and create awareness and outreach within their ecosystem. Assignments are used to put theory into practice to check the understanding of QT concepts; hackathons focus on applied knowledge, using the quantum knowledge of the community to create problem-solving skills and developing ideas or applications of QT as well as doing community projects, applying theory to practical questions and map out solutions. Some organizations offer quantum games to learn in a playful way:

> *“What we've been trying to do a lot is the educational games, […] trying to frame it in a sense of quantum rules […] and we try and take classical games that people know already and add in these quantum rules.”* (Participant 5)

Most of the grassroots organizations offer a broad mix of teaching and learning styles, also reaching different learners in their needs and individual situations. They do offline and online events to connect the network more broadly, offer learning opportunities to a wider audience and

keep the network connected: *"We are also trying to have more online activities. […] just a small thing where people gather. It helps us to stay in touch, stay active."* (Participant 9)

Regional differences

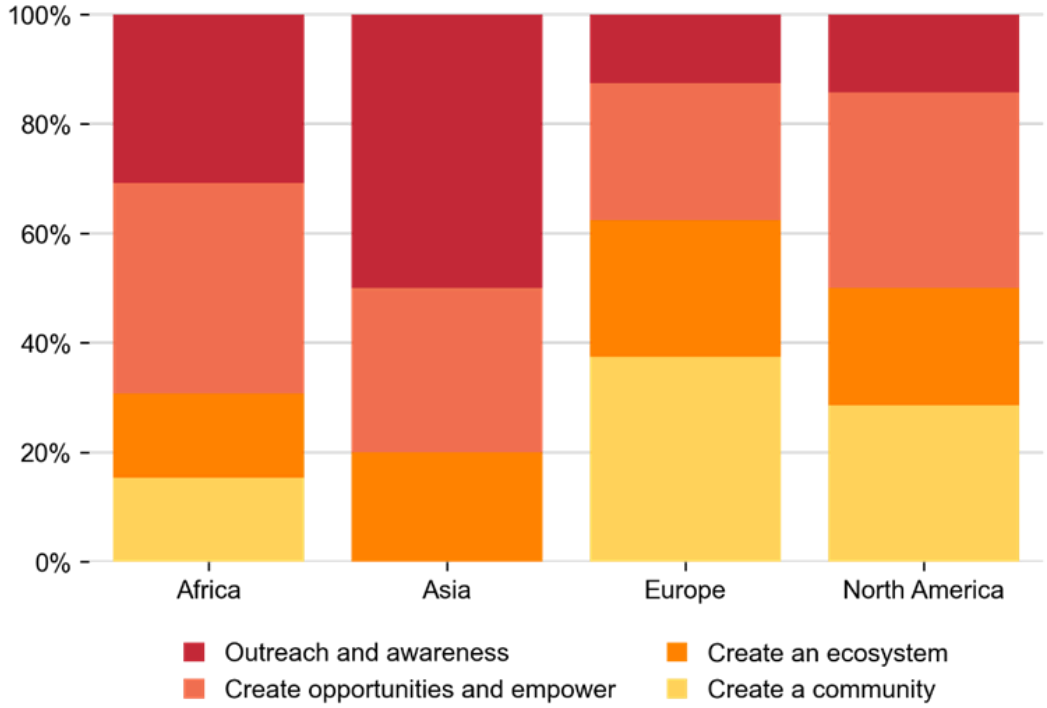


Figure 6: Comparison of goals according to region, education was omitted as there was no difference.

Comparing the data of the grassroots organizations from different locations around the globe, there are some differences in their values and goals. Comparing Africa and Asia with Europe and North America, there are differences in outreach and awareness. Countries with programmatic attention of QT in government, business, and education experience a stronger saturation of awareness in the ecosystems. Funding is an issue for all grassroots organizations, but the investments into QT and spending of funds are not equally distributed around the globe [11], leaving organizations from the Global South with the challenge to raise awareness and spending time educating decision-makers about QT, whereas other organizations from countries with higher investment schemes on QT can focus on community building:

> *"This is the 26th year of Africa Tech Festival, and this is the first year quantum computing is a topic. So, I feel it's a big step where Africa can get to where the rest of the continent will also get to about quantum computing. I feel it creates a whole large opportunity outreach […], because there'll also be start-ups and other companies and people from government. […] I think in the next 1 to 2 years, it's something that schools could be aware of. Maybe it would still be a process of working on how to create a strong workforce in the field at continent level."* (Participant 9)

> *“People will be more aware of the existence and use of quantum computing, not just as a trend, but also something that is for research and for industry.”* (Participant 12)

The challenge to create awareness towards governmental or economic or even educational institutions results in explicit membership skills that quantum grassroots organizations esp. from the Global South aim for people with technical expertise and experience in government and business, as the following quote shows:

“*We try to have people on the team who are more technical to approach the more technical groups such that they speak the same language. We've also had […] people work in government already, so they know how to speak the language that people in government would be more inclined to respond to. So, then they would lead those conversations. People are good with businesses also speak to the people who are more inclined to the business side and start-ups. So, it's a team effort.*” (Participant 10)

In consequence, quantum grassroots organizations from the Global South address different target groups. Most organizations address students of various ages as well as academics and professionals who want to learn, but in countries with lower investments and awareness of QT, the target groups are shifted toward decision-makers in academia, business, and governments. This strategic shift demands another degree of professionalization among the grassroots organization's members and fewer resources available to attract members and volunteers.

> *“We try to organize events where we could have more Africans exposed to the technology because quantum is not yet that popular across Africa, given that it's from the 55 countries, I don't think more than 20 have a very strong quantum computing presence. So, it takes communication and networking. […] building the collaborations, we also try to get government involved. So sometimes it's trying to organize and set up those conversations with people in government, and I also try to get people in academia because they have the most access to the students who are the future, given that Africa is a large youth base.”* (Participant 9)

Another reason, why countries from the Global South have a greater focus on outreach and awareness is their lack of accessibility. That is an essential driver for global grassroots organizations, providing content within the global community and bridging the gap between people who have access to exclusive learning materials, like IBM Qiskit or quantum computer simulators and those who have not.

> “*Sometimes you don't have access to the information because of where you are located. But since members are in the diaspora, if they are in America, they know what some of the programs that we could benefit from are happening. So at least we have that to keep us updated on activities and events and also just the progress that's happening in the ecosystem.”* (Participant 9)

Accessibility also refers to availability in different languages, showing that such barriers are especially important to global grassroots organizations and those in countries where English is

less widely used. They want to reach people in their own language and introduce them to quantum content. The following quotes are from a global organization and a Brazilian one:

> *“I think accessibility is definitely a big one. The fact that we have people from everywhere, a lot of our content is translated into multiple languages. It's not just English. We have Spanish or various Indian languages and sometimes we have Arabic and our channels internally. Also, we have different language channels where in the past we've had events in different languages as well. I think that speaks to accessibility is just because English may not be your first language. And for many people, Asian, it's not their first language. We don't want that to be a hindrance. We're trying to eliminate as many boundaries as possible.”* (Participant 2)

> *“The people speak Portuguese, there's not that many people speaking English. […] English is supposedly the universal language, but I particularly care about producing stuff in Portuguese, because my main thing about science communication is that I think there is a big gap between general public and what physicists think that is accessible.”* (Participant 16)

Limitations

The study's unique focus on grassroots organizations, while valuable, does present some limitations. For instance, the selection of these organizations was confined to those operating in English, thereby excluding potential participants from Latin America and the Asian region, including China, Japan, and South Korea.

The response rate of the organizations for the survey and interviews was average at 30%, but due to the size and distribution of the member regions of the global organizations, there was a potential knowledge gap as to whether most of the organizations’ members shared the value set that was mentioned by the participants. We did not find evidence in the focus groups that there is much difference, but the focus groups in this study were rather small, with only two different members of global organizations.

While regional characteristics were indeed identified based on the interview data set, it's important to note that the study's design did not specifically target regional differences. As a result, the data set is not fully representative, with significant gaps in regions such as the Middle East, China, and other countries in Asia and Latin America. However, this presents an opportunity for future research to fill these gaps and provide a more comprehensive picture.

Discussion

The study's results show grassroots organizations' efforts to democratize education and its potential benefits for creating ecosystems, diversifying workforce development, and creating quantum literacy and awareness. Comparing their goals and values shows their strength in democratizing learning opportunities for people around the world, making quantum knowledge accessible, and understandable. The organizations connect private initiatives, such as IBM's Qiskit, to their members and make quantum knowledge available to students, professionals, or the local public in general. Quantum grassroots organizations use a variety of narratives to

make QT accessible to a wider audience, to help build a knowledge base that is not just physics and to promote an inclusive language for the purposes of utilizing QT [5]. As Coenen et al. write “Language matters, because the way we talk about things sets a horizon of expectation for how we go about doing things.” [2], which in the context of the different educational narratives and teaching methods employed of quantum knowledge offered by grassroots organizations is a valuable contribution to literacy efforts and worth exploring further. Also, the grassroots do not prioritize high quality educational materials, so their level of quality in educating students, professionals and the general public as more organizations are established remains an open question and is certainly worth exploring further.

By disseminating knowledge of QT to people of diverse backgrounds and origins, grassroots organizations play an important role in addressing the shortage of a well-trained quantum workforce [19]. Besides the fact that there are strong efforts to expand the quantum workforce through national programs, grassroots organizations contribute to addressing the quantum workforce shortage through education, by popularizing and attracting people to quantum who might not have chosen this field of interest and by creating a support network along the learning journey. By reaching out to people of all genders and backgrounds, grassroots organizations can help to diversify the future quantum workforce, benefiting societies and economies [23]. In addition, grassroots organizations build bridges while countries impose trade restrictions and focus on national agendas. Organizations from Africa or Latin America address leadership and target decision-makers to create a local quantum ecosystem that creates a need for economic and political programs, education, and funding for QT. While grassroots organizations may have little impact on changing the political and technological division between the ‘haves’ and ‘have-nots’ [15], global quantum grassroots organizations build bridges by connecting and distributing available content to countries and members with fewer technological resources and opportunities. Through their own efforts to participate in the worldwide developments of QT, they work to reduce the disparities between nations and benefit the entire quantum community [4, 16].

Grassroots efforts align closely with the values of responsible research and innovation (RRI), which supports the inclusion of a wide range of perspectives in R&D and innovation processes, as well as the consideration of ELSI of quantum. Even though impact and social responsibility were not mentioned as prior values, the organizations provide a platform and community where people with different backgrounds and needs engage in discussions about how QT could be approached and be utilized in future and anticipate different opportunities. They share their ideas in hackathons, learning events, and the creation of quantum applications, allowing for the exploration of previously inaccessible spaces of opportunity [4, 5].

The correlation between media attention to the quantum advantage and the creation of new organizations suggests that the hype around QT leads to increased public awareness and a positive impact on the number of organizations and members. However, the rise of QT performance has also attracted the interest of policymakers and entrepreneurs, leading to increased national investments and newly funded companies [10], which has led to a recalibration of expectations among scientists, emphasizing RRI and its impact on society [4, 34]. How the change of hype and narratives around QT influences grassroots organizations’

values and motivation remains an open question [34, 35], as this study mostly spoke with first-generation founders and mostly long-term members. Moreover, due to the fact that a large number of new organizations were created during COVID-19, it remains an open question how the end of the pandemic will affect the community of grassroots organizations, their further establishment in the ecosystem, and the growth of new organizations.

Finally, despite the positive effects of grassroots organizations on quantum ecosystems and the future development of QT, as well as societal effects by incorporating shared values of inclusivity, diversity, and accessibility, the organizations are in the beginnings of their journey, and it is not yet clear how they develop further by managing transitions of founders and long-term members, stepping into their own careers, leaving organizational development and change to new generations. Also, the COVID-19 pandemic has passed, which has been a great accelerator for virtual meet-ups and online content [29], and openness of knowledge exchange on a global scale seems to fade. However, it is not yet clear how this affects the connectedness and strength of global and local communities, making the grassroots organizations potentially vulnerable.

Conclusion

In conclusion, the grassroots organizations contribute to democratizing of quantum education, making quantum knowledge accessible and understandable, to learners of all backgrounds and to countries with less resources. The numbers of founded organizations is increasing, addressing more quantum knowledge to quantum enthusiasts and attract potentially more learners worldwide. Through their work they support bridging the quantum divide, fostering quantum literacy and awareness also among the public and enable participation and engagement of diverse perspectives in the quantum ecosystem and future QT development.

Grassroots organizations address the shortage of a quantum literate workforce, by offering a broad mix of educational resources and teaching methods, providing platforms for discussions and explorations as well as their strong focus on diversity and inclusion. They bridge current gaps for non-STEM students as well as learners from different backgrounds, approaching minorities, inviting them into the quantum realm, widening the potential future workforce. Their efforts on diversity and inclusion are beneficial to the quantum ecosystem, but also to societies in general, increasing a broad knowledge base, which potentially results in higher trust-building, responsible innovation efforts, ethical, legal, and social considerations and even more diverse quantum applications.

Despite the positive impacts, these organizations face challenges, such as managing transitions among founders and long-term members and adapting to post-pandemic shifts in global connectedness and knowledge exchange. Also, while the hype around QT has spurred media attention, public awareness, and national investments, it remains to be seen how the changing environment towards market formation and rivalry, will influence grassroots organizations' values and motivations. As these organizations continue to evolve, their ability to sustain and grow with their core values will determine their future impact on the global quantum ecosystem.

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Conference Proceeding 1.9: Games for Quantum Physics Education[117]

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Abstract. As the second quantum revolution comes to pass with its potential to revolutionize our lives, it becomes increasingly relevant to educate the public about quantum mechanics. Quantum literacy is also a formidable challenge an opportunity for a massive cultural uplift, since it fosters the possibility for citizens to engender their creativity and practice a new way of thinking. However, quantum theory is highly counterintuitive, manifesting in a reality we have no direct experience of, and represented by mathematically difficult formalisms. Here, we propose that games can provide a playground for engaging forms of experimental and symbolic literacy accessible to anyone. We discuss the theoretical foundations underlying this idea in the framework of a global educational strategy, illustrate existing examples of its implementation along different dimensions related to educational, citizen-science, and age-related contexts, and envision future challenges.

1. Introduction

The rapid change in science and technology witnessed in the last decades has significantly increased the awareness of decision makers and education stakeholders of the need to strengthen the connection between research, education, and outreach. As the first experiences of scaling up the latter are being evaluated a shift in focus "outreach" to "engagement" is starting to take place, in order to reflect the need for a two-way interaction where all parties can contribute to and benefit from the learning process [1].

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Along these lines, increasing public awareness of quantum physics is becoming a priority as an extraordinary opportunity to develop general physics intuition and innovate physics learning/teaching processes in all school and University degrees. This is especially true amidst the second quantum revolution [2], where new Master and Bachelor of Science programs for quantum information and engineering are flourishing worldwide [3-5], and the recent development of a quantum competence framework has laid out a set of knowledge goals for the future quantum-literate workforce [6]. In fact, while quantum technologies and solutions are being developed for sensing, simulation, computing, and networking purposes, there is the potential for incredible economic development with enormous potential societal impacts from revolutionizing our daily lives to deeply changing the labor market [7]. Both in order to ensure the education recruitment pipeline and to build positive public attitudes of adoption, there is an urgent need to build up awareness on quantum technologies, their benefits and potential drawbacks, and increase the level of quantum literacy among students and general public. Also, like other forms of socio-scientific, collaborative knowledge creation processes, collaborative work around building Quantum Science and Technology (QST) solutions represents a great opportunity for smart community building, as it trains to out-of-the box thinking, with creativity and originality [8]. Scientific thinking hinges on analyzing facts and creating understanding, then formulating these with dense mathematical language for experimental verification, fact checking, and further development. Within classical physics, learner's intuition can be educated via classroom demonstrations of everyday life phenomena. Their understanding can even be framed with the math suited to their instruction degree. For quantum physics, however, no table-top experiences are available of microscopic phenomena, even if they are so beautifully explained by quantum mechanics with its advanced formal machinery. Thus, we cannot easily rely on experience nor math to inform our quantum-physics intuition building [9]. One related challenge is that quantum mechanics is counterintuitive and perceived as one of the most bizarre physical theories, involving a change in paradigm perhaps more radical than any other in the history of human thought. As Bohr said, “Anyone who is not shocked by quantum theory has not understood it”. Thus, in school and outreach contexts educators risk providing only conceptual-history storytelling or evanescent tales misled by the use of familiar analogies, which can become a breeding ground for misconceptions. In undergraduate courses, educators risk to provide preeminently formal understanding, ineffective to develop intuition, in fact a roadblock for engagement in the broad student population [10].

Given that we cannot rely on neither experimental or mathematical literacy, nor on everyday intuition, the only one way out seems educating everyone’s intuition in quantum physics by resorting to engaging alternative or complementary forms of experimental and mathematical literacy. More recent discussions focus on the use of the spectacular potential applications of quantum technologies, in particular on quantum computing, as effective means to motivate the introduction of quantum physics concepts and tools [11-18]. This is not surprising, considering that the quantum technologies literature has grown by nearly three orders of magnitude in the last two decades [14], and quantum computing has been receiving increasing attention in view of the possibility of approaching in some future the realm of the so-called quantum advantage

[15], i.e. the point where a quantum computer will outperform the most powerful classical computer on a given useful task. Here, we propose that games may provide an avenue to connect quantum technology concepts with concrete user interactions and investigations, and explore the extent to which this idea can be effective.

In games, players are engaged to overcome their limits and rewarded by skill challenges independently of backgrounds and disciplines, what can amplify motivations and unleash creative thinking as everlasting resources for community development [16,17]. Using games as broadly accessible and engaging entry point to complex topics, related educational material can then be developed, scaffolding the build-up of the desired competences.

General engagement and sense of purpose can be amplified in citizen science efforts in which citizens are empowered to actively contribute to the solution of concrete research questions presented in an accessible, often gamified, form [18, 26-28]. According to estimates, by the age of 21 the average US citizen has spent the equivalent of a 40 hours/week full-time job for five years playing videogames [19]. Games are characterized by goals focused on epic and emotion-activating adventures, a set of rules that define constraints but also opportunities to unleash creative thinking that fosters the overcome of skill limits, a feedback reinforcing motivations, a voluntary participation allowing players to leave or keep trying without fearing the consequences of repeated failures. In fact, games are extraordinary tools in pedagogy [20] and competence development [21] and foster community building: a non-perishable and untapped source of extremely valuable goods in terms of problem solving. People have started to wonder if this enormous amount of human brainpower can be harnessed for tasks beyond the grasp of current computer machines. One answer is by designing Games With A Purpose (GWAPs). As one example, citizen science has become a powerful approach in research, educational, and decision-making contexts [16,18]. Even if these ideas might sound extravagant, there are many successful examples of GWAPs for education in classical and quantum physics, including those which tackle research problems [22- 26,28] starting from the seminal Foldit experience down to proposals aimed to integrate human and machine minds to solve otherwise intractable quantum problems [26-29]. In the quantum domain, Quantum Game Jams [30] are often used as contexts to conceptualize/develop games, providing ideas, usable prototypes, and educational opportunities in tandem. Quantum games have been proposed also as a context to learn quantum computing without many prerequisites [31] and as an experimental environment for introducing learners to quantum mechanics [32]. It has been noted that allowing scientific experimentation is an important part of fostering scientific inquiry [33], and in the quantum realm, such experimentations are not readily available for the majority of the population. Hence, properly designed games [34] can be used to close this gap to some extent.

We believe that it is timely to dig into this topic in systematic, critical, and rigorous manner to unveil opportunities and criticalities, and elaborate through a theoretical and practical perspective various physics education research tools. This work aims to offer an open-minded inspection of the current status and hereby stemming perspectives, discussing in depth and width the challenge of using quantum games as tools for quantum physics education.

The paper is organized as follows. We start in Sec. 2 by addressing in general the questions of what makes any game ‘quantum' [35] and of how their effectiveness for education can be assessed. In Sec. 3, we illustrate the answer to these questions as provided by the ScienceAtHome research and education group at Aarhus University [36], incorporating the dimension of how humans think about quantum mechanics regardless of their educational level and highlighting potential and practical implications in increasing players' knowledge of quantum research and technology in society. In Sec. 4, we explore the question whether or not there is a lower limit to the age for which one can design effective games for quantum physics education by reporting on the more recent class-workshop experience given by Particle Physics in Primary Schools (PPPS) [37-40] wherein we incorporate arts and crafts and creativity to convey a scientific and inspirational message. Sec. 5 elaborates on the question whether and how the use of quantum games as educational tools can be framed into a global and strategic vision to root a durable educational and societal change by illustrating the approach adopted by QPlayLearn [8]. We conclude by discussing in Sec. 6 the methodological and practical challenges that future work in this field should address, before proceeding to a content summary in Sec. 7.

2.What makes a game quantum?

Players interacting with games constructed by classical game engines reinforce their experience of how the classical world operates. A similar approach can be adopted for quantum games to build an intuition about the quantum world. Therefore, it is important to explore which aspects, actions, engine properties, and integration methods are most effective for building up players' intuitions.

We have found that more than 100 ‘quantum games' have been developed around the globe, and most of them are freely accessible [42]. Given the existence of such games, with the increased presence of global online communities (also due to the COVID-19 pandemic), we believe that now is an opportune moment to explore the possibilities provided by utilizing quantum games for education and outreach/engagement purposes within the second quantum revolution. Moreover, developing high- quality quantum games that foster scientific inquiry and raise quantum literacy, could also help in bridging the divide between society and the quantum technologies possibly reshaping our future, which would otherwise enhance inequalities in even more severe manner than the already existing digital divide does [43, 44].

In this context, answers to the following questions emerge to be timely and prerequisites to any further reasoning: (i) what is a quantum game and what makes any game ‘quantum’? (ii) can there be a ‘quantization method' of classical games, which turns regular games into quantum games? (iii) can we assess the effectiveness of different quantum games with the same assessment tools and, if so, how should these assessment tools be developed? We answer these questions, by referring to the preliminary findings of a summer project organized under the QIntern2021 [46] program put on by QWorld [35].

Here, a *quantum game* is defined as "*a computer (or video) games with one or more of the phenomena from quantum physics embedded in their game mechanics"* [46]. One can also extend this to cover educational (or serious) games directly aiming at introducing quantum mechanics to a wider audience or enable/support teaching of quantum mechanics. However, it might be beneficial in the long run for quantum games to become a concise and self-explanatory concept, the usage of the term should slowly be limited to the one or the other. Educational games can be specifically called as educational quantum games following the definition raised in [39]. Furthermore, games that are capable of running on actual quantum-computation hardware may be accepted as quantum games, since the mere fact that they are able to run might indicate some quantum mechanics is embedded in their game mechanics.

If we consider quantum games within the context of game mechanics, a sort of 'quantization method' can be developed for classical games by introducing or transforming an essential game mechanic to cover a phenomenon from quantum physics (such as superposition, entanglement, non-commutativity, interference, etc.). In this sense, the quantum version of the game will be essentially different from the classical version of the game, which alters the user experience. This can be seen as an initial step towards informal self-learning by players as they learn to work within the new strategic space presented by the 'quantization' of an otherwise familiar game.

Finally, the effectiveness assessment for quantum games is a topic requiring special expertise from the educational research domain. Quantum mechanics is a wide topic, and things get even more complicated as we aim to utilize these games to enable learning, as this, in the long run, can support the development of quantum technologies. Core competencies for quantum technologies are still not fully understood in the literature, and further studies are needed [47,48]. Therefore, developing assessment tools for quantum games contains particular difficulties, and the possibility of assessment tools that can be used for any potential quantum game seems, at the moment, to be highly unlikely.

Following the description of a quantum game above, in the summer of 2021, with a team of interns, 120 quantum games have been collected and classified. Access to the games and relevant documentation can be accessed via Ref. [49]. We mainly collected games from publicly available resources. Of all the games surveyed, 97.5% are free to play, 39% can be played online while 61% requires some sort of download. We identified that only 10% of the games are mobile friendly while almost 90% are for PC or Mac devices. Meanwhile, 23% of the games developed for PC or Mac devices are playable via browsers, indicating that they are also playable on some mobile devices.

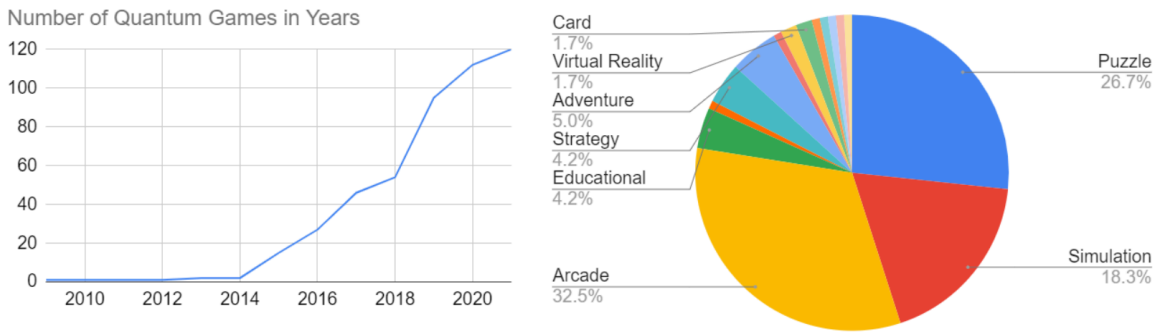


Figure 1. Total number of quantum games in years (left) and their type of classification (right).

In addition to the analyses above, we checked some basic properties related to the games. Firstly, in Fig. 1 it can be clearly seen that development of these games became popular following the first Quantum Game Jam organized in Finland in 2014 [50]. Also, it can be seen that most of the games are of the puzzle, arcade, and simulation types. However, it can also be seen that a wide range of diversification can be observed, which might indicate that quantum game developers are experimenting with game types and mechanics, in search of novelty.

In Fig. 2 we show two properties of these games, (i) whether they have a classical counterpart of the game and (ii) whether or not the game has been developed during a hackathon or a game jam. It can be seen from the figure that most of the games do not have a classical counterpart, which means most developers aimed for creating novel games instead of quantizing existing games. However, 41% of games are quantized, which is not insignificant. Similarly, most of the games were developed during hackathons or game jams, but the ratio of independently developed games (44%) is again not insignificant.

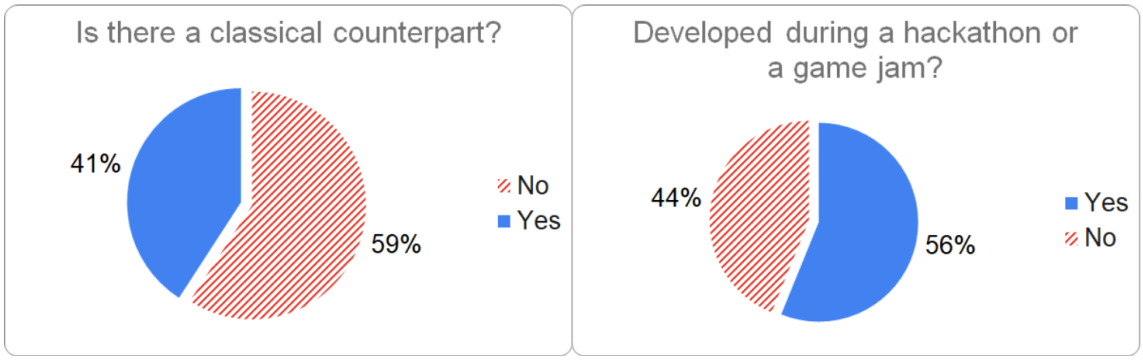


Figure 2. Ratio of games with classical counterparts (left) and developed in hackathon/game jams (right).

3. How do we think about quantum mechanics? The ScienceAtHome case study

While quantum games can take many forms, from games developed using quantum computers to purely educational games aimed at teaching the player something about quantum mechanics, answers to questions (i)-(iii) outlined in the introduction require prior reasoning on how amateurs and experts approach and solve quantum problems, tapping, in some sense, into human intuition about a very unintuitive subject. In this section, we discuss the answers provided by the suite of quantum games and initiatives developed by ScienceAtHome, a research group at Aarhus University aimed at exploring how humans think about quantum mechanics regardless of their educational level in physics. In addition, ScienceAtHome seeks to educate players on the relevant aspects of quantum mechanics that apply to the games they play. To this end, some of these games include citizen-science-based tasks, where players contribute to cutting-edge quantum research increasing knowledge of quantum research and technology in society, thus building quantum awareness and quantum literacy. All games and surrounding educational material can be found online [55].

3.1. Quantum Moves 2

In *Quantum Moves 2* (QM2, Fig. 3 left), the player is tasked with solving relevant problems in the control of a quantum state consisting of one or many atoms, and the quantum state is represented as a liquid-like object that sloshes around as the player manipulates the system in which it resides. It is found that player solutions can provide valuable information to researchers [28], even in the face of the unintuitive nature of quantum mechanics. For example, Ref. [28] shows that players sample a different part of the control landscape (i.e., the space of all possible solutions to a given problem) than some algorithms. Furthermore, QM2 has been used in numerous educational scenarios, including a randomized control trial on research games in Danish schools [59], where students play QM2 and learn about both classical and quantum physics.

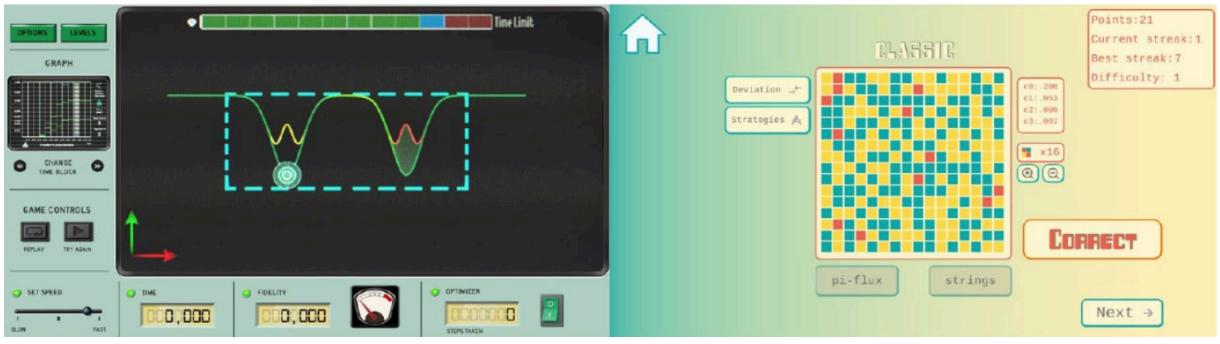


Figure 3. Screenshots of Quantum Moves 2 (left) and the Quantum Mønster (right)

3.2. Quantum Mønster

The *Quantum Mønster* (Fig. 3 right, Danish for “pattern”) is being developed to help physicists understand the theories underlying the behaviour of fermionic particles (like electrons) in

ordered potentials, which is useful for the study of high-temperature superconductivity, among other things. As with QM2, the *Quantum Mønster* is aimed at understanding how amateurs and experts think about the problem at-hand, with the ultimate goal of helping neural networks to better classify systems that behave according to the different theories of fermion dynamics.

3.3. The Alice challenge

In 2018, the laboratory has been opened up to the general public for the *Alice challenge*, wherein citizen scientists used a gamified interface to optimise the cooling of atom clouds used for quantum simulation experiments. The production of these ultracold atom clouds, which are also a first step towards many quantum sensing and metrology experiments, require a lot of specialized training and equipment to produce. It is found that with an intuitive interface that pared down the required information into an illustration of just what was absolutely necessary, the amateurs were able to make larger clouds than the experimental experts had previously [26]. In general, the experimental methods used to open the lab up to external users required an advanced queueing system [56]. Hopefully, the description in Ref. [56] can guide others who wish to make their experiments remotely accessible to students, researchers, and citizen scientists, as this equity of access can help to bridge the gap between those that can gain firsthand training on advanced quantum experimental systems and those who cannot directly access them.

3.4. Other games

The same idea of understanding how people work with quantum systems rings true in the *Netty* game, a prototype of which can be played at [57]. Here, players are tasked with helping to solve problems regarding the organization of quantum spins in networks; the minimization of the energy of the system
is an NP-hard task for classical computers. The *Rydbergator* [58] has also been developed, a gamified tool used for understanding how interacting atoms organize themselves in the presence of highly-excited Rydberg states, which prevent more than one atom from being excited within a certain distance of a highly-excited Rydberg atom.

4. Is there a minimum age? The Particle Physics for Primary Schools project

It is well known that serious games are extraordinary tools conceived in pedagogy since the seminal idea from Montessori that “playing is children’s work” [20] to develop their emotional, cognitive, motoric, communicative, relational, and creative thinking [21]. One might then wonder whether games can be used to create forms of quantum physics education in childhood, and down to which age one can dare. In this section, we report on the development of a more recent experience aimed at divulging particle physics research concepts to primary school children [37-40]. Besides the positive results obtained from children feedback, this experience has a methodological significance, as it represents a fruitful example of a collaboration between academia, school teachers and professional outreach officers.

The project stems from the mounting evidence that early school years are critical for children education and are influential for their later development, including their personal attitude

towards science and its perception [41,42]. The project rationale is in the compelling need to modernize the science content of both primary and secondary schools, taking modern 20th-century physics to the classroom, with its fundamental questions, in order to fascinate and inspire wonder in young students, regardless of their socioeconomic or cultural background. The common perception of 18th century classical physics as a set of well-established concepts doesn't help to raise the interest of young minds towards science; most importantly, it doesn't foster or promote the message that science is a dynamic process to which individual children can directly contribute once they become adults. This message is, however, essential to establish a personal connection between children and science and a sense of ownership of the subject, with the ultimate goal of increasing the society science capital. Science capital can be defined as the sum of all the science-related knowledge, attitudes, experiences and resources that an individual builds up through their life [43].

The project was developed as part of a school activity for primary schools in the UK. The main aspect of the project is a workshop, led by researchers and/or teachers, to be performed during class lessons or as an after-school club. The workshop is complemented by enrichment and feedback activities. The project also includes an aspect of teacher training and continuous development so that teachers involved in the project can gain the required scientific literacy needed to teach the relevant concepts to their students. In order to enjoy and profit from the full workshop, the recommended requirement for the student is the ability to read and write at a basic level.

The workshop starts with an introduction to the world of elementary particles, with practical demonstrations of key concepts to promote students 'active participation. The introduction is followed by a range of creative enjoyable activities, with an increasing degree of complexity and physics content: the activities range from making models of elementary particles inspired by their characteristics (such as mass, electric charge, and particle families), to card games that facilitate the assimilation and consolidation of notions and concepts. The games explore more challenging concepts relating to the quantum world, such as particle interactions, matter-antimatter annihilation, and the beauty of Feynman diagrams. The gaming aspect has been identified as key to facilitate the learning process of young children [44]. The workshop includes both individual and group activities, and concludes with a group activity where children explain and demonstrate their work and creations to fellow students and teachers; this part facilitates and promotes the communication aspect of the project, while allowing checks of the learnt concepts and ideas.

The project has been recently extended to schools in Greece and Italy. The arts-and-craft aspects of the workshop are crucial to transmit the message that there isn't a rigid dichotomy between art and science, and that creativity is in fact an essential part of the scientific process. Emphasis has been placed on the need to convey a correct and detailed scientific message, albeit one that is simplified and tailored to the audience using metaphors and similitudes. Finally, special care has been taken to avoid limiting the freedom of creative expression, allowing children to use their favorite art media (i.e., drama, dance, poetry, narrative, illustration etc.) for most of the activities.

The follow-up enrichment activities have been left to the teachers with suggestions from the researchers, and these allow students to explore connections between physics and other sciences, and between science and other disciplines. As an example, the aspect of citizenship in science can be addressed when speaking about international science collaborations that are natural in experimental particle physics research.

The aspect of teacher and ambassador training have been developed over the years, to make the project scalable and sustainable, with the help and collaboration of several scientific institutions such as the Institute of Physics, the Ogden Trust and the STEM Ambassadors. Resources have been developed to this end, consisting of a teacher manual and educational material to assist the delivery of the workshop (see links in Refs. [37-40]). As a result, a sizeable number (in the hundreds) of primary teachers have been successfully trained to deliver the workshop in England.

The impact of the project has been verified by collecting feedback from students and teachers before, during and one month after the project. This includes measures of how enjoyable the project was, indicators of specific impact, such as quantity and quality of scientific content assimilated and remembered, and changes in behavior, attitude and perception towards science have been recorded. The results are positive, indicating clear evidence of a positive impact on students. However, work remains to be done to assess whether or not the participants have truly internalised the physical concepts illustrated in the games; this lies outside of the scope of the work presented here.

5. Incorporating quantum games into a global strategic vision: QPlayLearn

Hinging on games as educational tools without a global vision of the educational frame may easily fail to produce a real cultural change we aim at: we cannot root these games and tools (and the interactions they provide) into a durable educational and societal transformation.

In this section, we report on the global strategic vision implemented in QPlayLearn (QPL) [8,45], an online platform conceived to explicitly address challenges and opportunities of massive quantum literacy. QPL was born from a group of scientists passionate about quantum science who firmly believe that everyone can learn about quantum physics and its applications, regardless of their age and background. To this end, QPL develops multimedia tools that aim to enhance the learning process effectiveness, through fun and accessibility, while remaining rooted in scientific rigour. As a strategy for massive cultural change, QPL's mission is to provide multilevel education offering diverse content for different target groups, from primary school, to university students, to quantum science enthusiasts. It is also addressed to companies interested in the emergent quantum industry, journalists, and policymakers needing to grasp what quantum technologies are about.

Inspired by the multiple intelligences theory [60], QPL holistic perspective stems from the recognition that different types of intelligence dominate the learning process of each person. Thus, the platform is conceived to accompany users in their quantum journey via different paths aimed to: (a) build intuition and engagement via games and videos; (b) understand

concepts via accessible and scientifically accurate descriptions, graphics, animations and experiments; and (c) acquire formal understanding through the math. Each user can begin from the approach felt easier, and then possibly explore the others.
Eventually, it is the combination of the different manners that shifts and expands understanding.

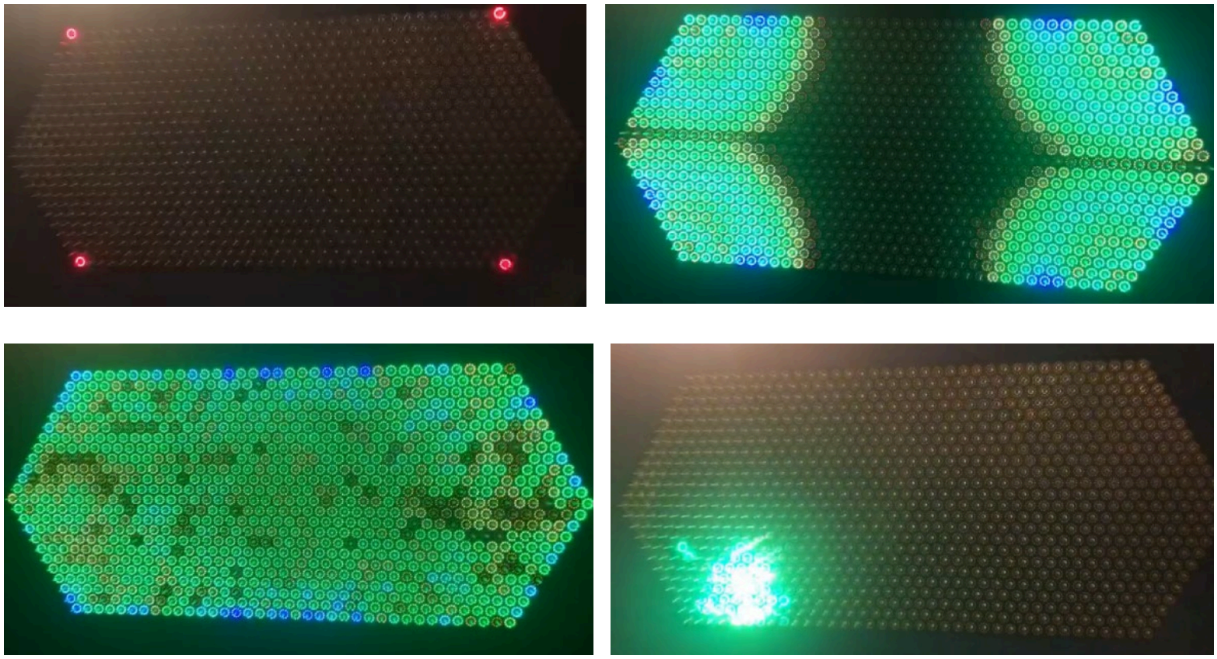


Figure 4. Screenshots from the Quantum Jungle, visualizing the time evolution of one quantum particle. After touching the springs, the quantum particle is created in a superposition state (top left). The probability from computer simulations of the Schrödinger equation evolves according to a quantum walk (top right, bottom left), and is visualized via switching on of LEDs with proportional intensity. Later spring touch is interpreted as a measurement action, visualizing the collapse (bottom right).

In the Play section, games are used to expose the users to several quantum concepts. In the Discover section, experts explain concepts with short videos, using analogies, experiments or deductive examples. Short animations (*Quantum Pills*) explain concepts at different understanding depths, for experts and amateurs. The Learn section enters the formal core of quantum theory, devoted to a more expert audience. In the Apply section, concepts can be practiced by running code samples on real-world quantum devices. Finally, there is a space dedicated to science-based art projects, where learning proceeds via the preferred user's artistic language, involving creativity at its best: examples are *The Photonic Trail* game [61], combining art, fantasy storytelling and quantum optics elements, and the *Quantum Jungle* [62] (Fig. 4), a 6 m^2 interactive installation in Pisa with 1000 springs and 12000 LEDs, by artist and computer scientist Robin Baumgarten, visualizing the time evolution of a quantum particle. In this context, games are one of the tools that stimulate users' interactive participation in building intuition about the counterintuitive features of quantum physics. The QPL team has carefully selected games with specific concepts in mind to present to users. The aim is that everyone can approach some of the most relevant quantum properties and phenomena, such

as superposition, entanglement, tunnelling, etc., without any technical knowledge being required. The selected quantum games (see Table 1) have been developed by different authors in different contexts, reflecting the variety of quantum games currently available as defined in Sec. 2. In fact, some of them were developed during hackathons or game jams, e.g. *Potatoes Quest* or *Escape: Quantum*, while others have been developed within broader educational projects, e.g. *Psi&Delta* and *Particle in a Box* by the Design and Social Interaction Studio at Georgia Tech University. Note that quantum concepts are used in these games in different ways, from being part of the game mechanics to being presented in an educational context.

Table 1. List of Quantum Games currently available on the QPlayLearn platform, with the physical concept each game refers to and the names of the authors.

Concept	**QG**	**Authors**	**Link**
Quantum Physics	Particle in a box	Aditya Anupam, Nassim Parvin, Azad Naeemi	https://qplaylearn.com/quest-quantum-physics#section-1
Quantum States	Quantum Playground	Physicists: Guillermo García-Pérez, Sabrina Maniscalco, Laura Piispanen, Matteo Rossi, Boris Sokolov. Dev. MiTale	https://qplaylearn.com/quest-quantum-state#section-1
Qubits	Q|Cards> Online	Viktor Minin (Code, Game Design) Sonya Minina (Graphics, Game Design). QPL team	https://qplaylearn.com/quest-qubit#section-1
SuperPosition	Quantum TiqTaqToe	Evert van Nieuwenburg	https://qplaylearn.com/quest-superposition#section-1
Entanglement	Quantum Solitaire	James Wootton	https://qplaylearn.com/quest-entanglement#section-1
Quantum Meas.	Escape: Quantum	Taryn Allen, Steven Dunn	https://qplaylearn.com/quest-quantum-measurement#section-1
Wave-like Behavior	Psi & Delta	Aditya Anupam, Nassim Parvin, Azad Naeemi	https://qplaylearn.com/quest-wave-like-behaviour#section-1
Tunneling	Potatoes Quest	Francesco Baldino, Luigina Mazzone	https://qplaylearn.com/quest-
Quantum Tech	QWiz	Physicists: Matteo Rossi, Nicola Lo Gullo, Boris Sokolov, Laura Piispanen, Walter Talarico, Sabrina Maniscalco. Dev. MiTale	https://qplaylearn.com/quest-quantum-technologies#section-1

QPL is currently being developed along different directions, including progressive content extension often in collaboration with research groups/institutions, to story-tell their research in quantum science and technology, the development of multiple language versions, and the extension of the class of beneficiaries to 0-99 year old users together with pedagogy experts.

6. Discussion

Games are involved in a wide spectrum of human activities: as natural expression of the human behavior [63], as mathematical expression of human way of thinking [64], as economic behavior. As discussed in depth by the mathematician John von Neumann and economist Oskar Morgenstern in the groundbreaking text creating the interdisciplinary research field of game theory [65], games are connected to human abstraction and formalization: they are an end in itself, engaging, all-encompassing and fun. In fact, the perfect context to allow people to reason in unconventional manners. Playful moments have a significant influence in the development of the comprehension of a subject [66].

Quantum games can make a difference in contexts of limited experimental and mathematical literacy. In fact, a playful moment has a transitional nature between the concreteness of acting and the abstraction ability of thinking irrespective of action. The playful context of the game offers a decontextualization opportunity with respect to school activities. Playful de-finalization motivates and activates personal learning processes via the connection with playful-symbolic skills. The rules of the game, which are required, relate to the affective sphere, become a goal (work), and allow learning [66]. The transition from action to abstraction is an internal process, allowing to develop logical memory and abstract thought. Perception is the spring that pushes us to act for this transition, while the act of playing increases the degree of awareness related to one own's actions, the rules enhancing game attractiveness. Playful activity allows us to experiment by using different mind frames and/or living conditions with no prior conditioning [67]. The player’s vision of the world is thus expanded, while "[experiencing] the way of structuring thought towards the universe" [68,69]. Last and not least, games offer access to knowledge tools and to metacognition: it allows players to understand how physics operates.

7. Conclusions and perspectives

In conclusion, we have discussed the significance of using games designed with the purpose of education in quantum physics and technologies and as tools that can complement limited resources of experimental and mathematical literacy, or even substitute them when missing, depending on context and the type of storytelling [70]. We have reviewed the meaning of quantum games and addressed the essential design elements that they should possess, to engage the learner independently of his/her background and the teaching/learning process context, sustaining the experience of thinking about quantum mechanics, and allowing an assessment of effectiveness. We have illustrated one pioneering implementation of this idea, provided by ScienceAtHome, where quantum games are a useful environment for scaffolding both self- reflection and quantum knowledge. This is based on the design of a unique visual interface and means of interacting with a given system, allowing to both tap into what makes human thinking unique and educate the public via their participation in scientific projects. The intrinsic playful nature of games makes them effective independently also of age, and we have

also discussed the documented and successful educational path Particle Physics for Primary School, designed to familiarize pupils with the physics of elementary particles. Individual, on-purpose designed tools can certainly empower a teaching/learning process. However, the extent in general depends on the overall strategy where the tools are grafted. Here, we have illustrated the QPlayLearn vision, implemented in a free platform to tailor quantum-science educational processes on the many talents of diverse users, via resources based on multiple languages and symbolic forms. With this flexibility, QPlayLearn can be adopted by educators or outreach experts in diverse contexts, to build up quantum literacy and awareness, and facilitate a diffuse, massive cultural change. We believe this is an authentic priority and, in fact, an unprecedented challenge [71].

The current bottom line about quantum games for quantum physics education naturally leads to further questions. First, although defining quantum games is further explored in the literature [72], a systematic classification is missing of the elements that make a game usefully quantum in relationship to specific educational purposes, and different target audience. Second, a theoretical analysis is needed, to guide the definition of working strategies to use quantum games within a complete teaching/learning process and didactic experiment [73]. Answering these questions is necessarily prior to the design of suited assessment tools. Finally, one truly unconventional challenge concerns the conceivable level depth in *a priori* quantum-game design, to enhance imagination and creativity while efficiently channeling them into operational concept understanding. Exploring this aspect requires a widely interdisciplinary approach, including neuroscience analysis of the visual human mind.

Acknowledgments

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Book Chapter 1.10: Communicating Quantum Technologies in an Era of Mistrust and Misinformation[118]

Simon Goorney, Federica Beduini, Maria Bondani, Laurentiu Nita, Lydia Sanmartí-Vila, Zeki Can Seskir, Jacob Sherson, and Maria Luisa Chiofalo

Introduction

In this paper, we tell the story of a community effort to bring widespread quantum awareness to the general public through scientific outreach. The project, entitled Quantum Technologies Education for Everyone (QuTE4E), emerged from a large practising community of educators, academics, and industry representatives in the field of quantum technology with over four hundred members from forty-five countries. Coordinated by a dedicated action intended to unite disparate efforts across Europe (Quantum Technology Education – QTEdu), eleven pilot projects were established to address quantum technology education for universities, industry, high schools, and the public. QuTE4E was among the most ambitious of all the pilot projects, with the core aim being to develop guidelines for public communication of Quantum Science and Technologies, pioneering a research-based approach we call Physics Outreach Research (POR).

We believe that all citizens, regardless of background, position, and educational experience, should have the opportunity to be made aware and be inspired by Quantum Technologies (QT). Technologies such as quantum computing, simulation, sensing, and communications are already changing the world, for example, developing highly precise medical imaging (MetaboliQs, 2018) or materials that capture carbon dioxide (Wei et al., 2020). Public awareness of this field is essential for two reasons: first, because inspiration is the seed from which the future quantum workforce is recruited, and; second, because the individuals who are or will become policymakers, work at start-up companies, or hold public offices must know the implications of QT, rather than considering them distant concepts with no real application. In the present period of mistrust and misinformation around emerging technologies, aptly called the “post-truth” era (“The Challenge of the Post-Truth Era”, 2018) a research-based methodology to deliver outreach for emerging technologies such as QT is essential.

To develop practical guidelines for communicating QT to the public, researchers in the pilot project first needed to answer the following questions:

- What are the main challenges that need to be overcome in order to optimise outreach efforts?
- Which ideas and content should we include in our “story”?
- What should be our narrative approach to outreach, our “storytelling”?
- What kind of tools can educators use to support this storytelling?
- How can we reach the widest audience in practice?

[118] https://doi.org/10.51746/9789612972417

In assessing the challenges and content necessary for outreach, the pilot ran a Delphi Study to obtain community input, which is described in Section II of this paper. After that, a storytelling framework was developed, culturo-scientific storytelling (CSS), which is described in Section III. The CSS calls for the use of engaging tools to support the scientif- ic-thinking process, the most effective of which are described in Section IV. In Section V, we discuss the implications of CSS for developing an awareness of Responsible Research and Innovation (RRI) in the public. Finally, in Section VI, we conclude with an overview of the increasing scope of outreach in the field of QT, and lessons learned from the pilot project on how to conduct it most effectively.

Community input: challenges and content

The first step in developing practical guidelines for outreach is to understand what they need to cover. By identifying the primary challenges for outreach, we were able to research and suggest methods to overcome them. Knowing exactly which topic areas constitute the best use of the highly limited time of educators and science communicators is also essential, and we therefore addressed all of these questions in the QuTE4E Delphi Study. The study ran between September 2021 and June 2022, and aimed to gather insights from practitioners in the field of outreach and education for QT on the most effective ways to engage with different stakeholders and the most important content to include in outreach efforts. (For the full details of the study, see Seskir et al., 2023.) Below we summarise the method, results, and key implications for QT storytelling.

The Delphi method, developed in the 1950s, is a structured process for obtaining expert opinions on a specific topic (Dalkey & Helmer, 1963). It involves a series of rounds in which experts are asked to provide their thoughts on a set of questions, with the responses from each round used to inform the next. This iterative process allows for a more comprehensive and nuanced understanding of the topic as it enables the integration of a wide range of perspectives into not only the responses, but also the questions themselves. In the QuTE4E Delphi study, a group of experts from the pilot project itself were invited to participate in the preliminary round. This was followed by two more rounds, which were open to the general public but mainly circulated within the QTEdu and associated networks. In the final round, thirty-six participants from seventeen different countries participated. Two examples of how questions evolved with expert feedback between the preliminary and final rounds are shown in Table 1.

Table 1: Example of evolution of questions between the preliminary and final rounds

Preliminary round questions	**Second (final) round questions**
What kind of important problems will there be for the outreach activities in quantum technologies in the following five years?	Please rate the potential problems in terms of severity for the outreach activities in quantum technologies that may be encountered or still persisting (in the next 5 years).
Which essential concepts of quantum physics should be utilised for outreach activities in quantum technologies?	Please rate the concepts/approaches provided below in terms of their usefulness to be utilised for outreach activities in quantum technologies.

Challenges for QT outreach

In the preliminary round of the study, participants were asked open-ended questions prompting them to provide their suggestions for what they considered to be major challenges in the field of QT outreach. The experts in the first round were then shown these responses, and additional items were added by them. In the final round, the larger group of thirty-six participants were asked to rank by severity the nineteen challenges provided to them in the previous rounds. As the field is evolving rapidly, we considered two separate time frames: the present, and more than five years into the future. Results are shown below, normalised so that the highest-rated problems are assigned a value of 1.00

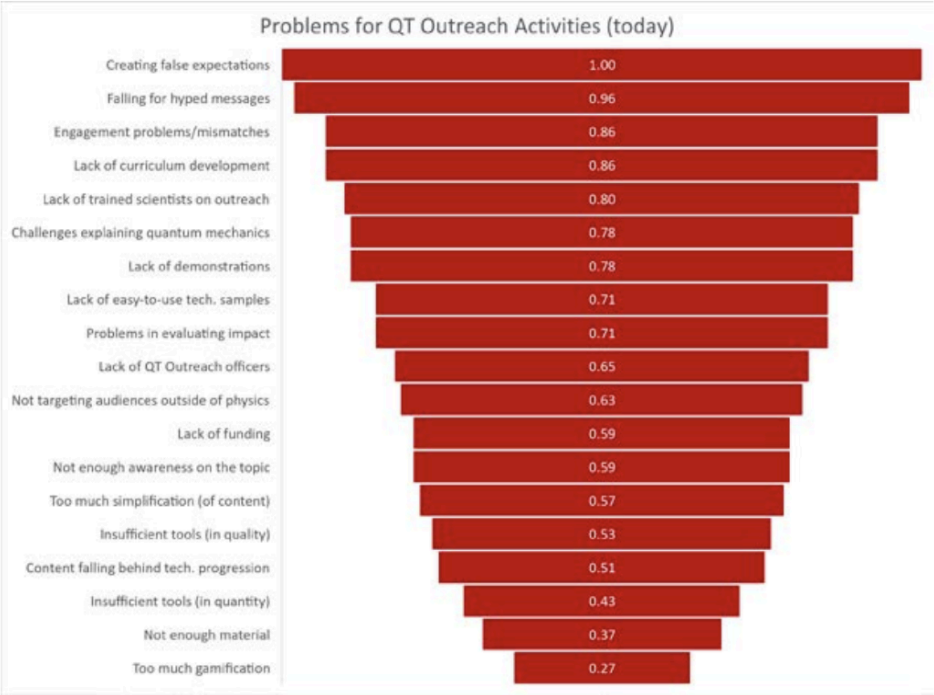


Figure 1: Challenges for QT outreach activities (present time), as ranked by participants in the final round of the QuTE4E Delphi study

Here we note several interesting findings relevant to practical storytelling. First, there is the concern about creating false expectations, which can lead to disappointment and erosion of trust. Second, there is a risk of falling for hyped messages and misinterpretation by non-ex- pert audiences, which can hinder understanding and progress. Both of these challenges call for outreach activities that are grounded in reality and show the real-world applications of the technology. Third, there are engagement problems and mismatches between the communities working in this field and their intended audiences, which can hinder effective communication and outreach efforts. Fourth, there is a lack of curriculum development for different target audiences, which can make it difficult to effectively educate and engage these groups. Finally, there is a lack of trained scientists who are skilled in outreach activities and methods, which can limit the impact and effectiveness of outreach efforts. These problems can be addressed with more dedicated efforts in QT outreach. Indeed, these issues are not unique to the field of QT, but are present in many scientific fields. In the present age of misinformation, we must find new ways of

communicating science to the pub- lic (Fähnrich et al., 2021). We believe that Physics Outreach Research (POR) and the modus operandi of the QuTE4E pilot project will significantly contribute to resolving these issues.

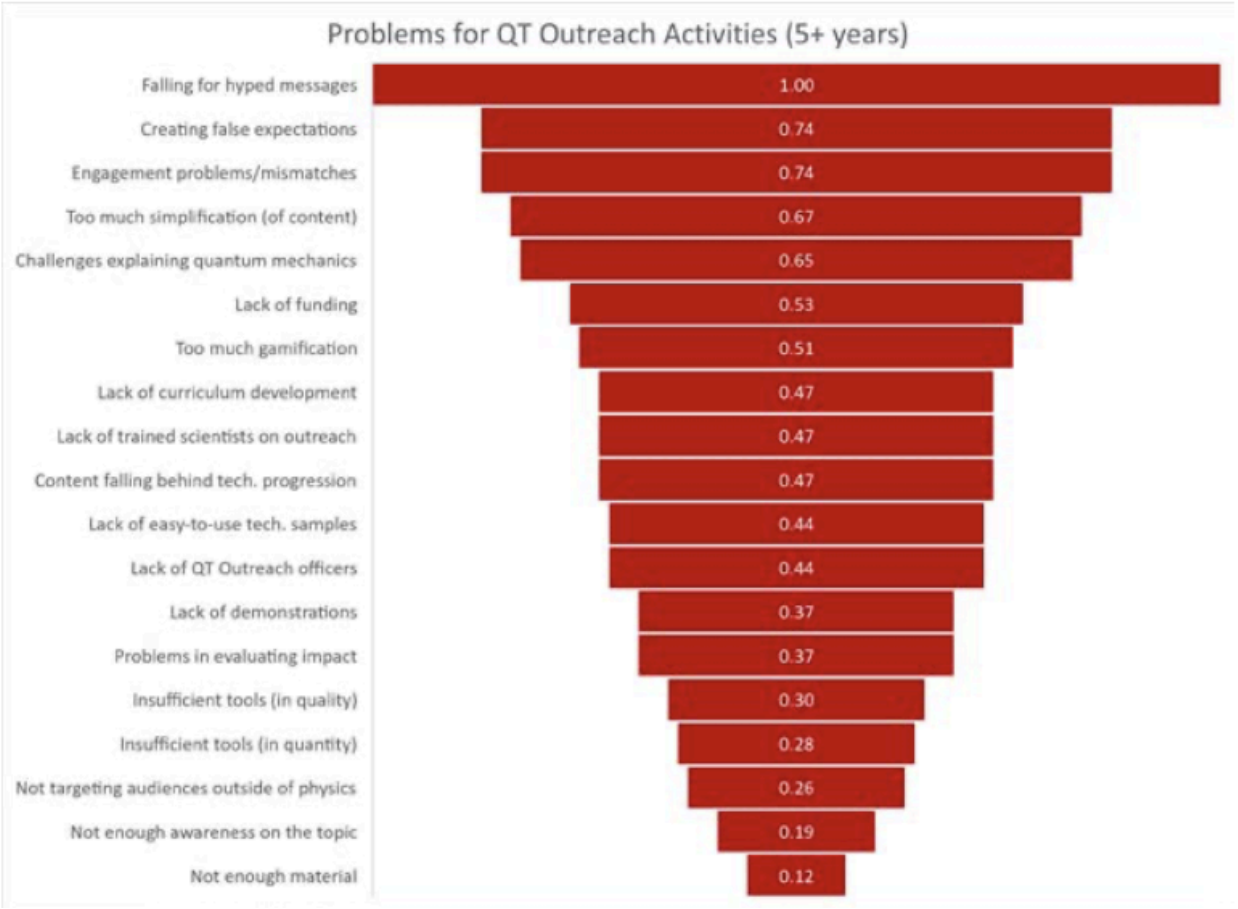


Figure 2: Challenges for QT outreach activities (five+ years into the future) ranked by participants in the final round of the QuTE4E Delphi study

Content for QT outreach

The second primary area of the study was focused on the perceived usefulness of various concepts and approaches for use in QT outreach activities, thus enabling practitioners to construct a narrative for outreach activities with specific topics in mind. As for the challenges, we first asked experts to suggest the topics they thought most important (in the first two rounds), and then asked participants to rank them by importance in the final round. The eight most important concepts as provided by EU and non-EU participants are shown below. In order to analyse their position within the narrative to be deployed, we used a conceptual tool known as the discipline-culture (DC) framework, first posited by Tseitlin and Galili (2005) to structure disciplinary knowledge. Here we describe it briefly and refer the reader to Goorney et al. (2022) for its use in structuring outreach activities.

It is clear that scientific fields have their own distinct discourses and narratives. This is obvious from just the titles of textbooks, courses, and journals, (Griffiths, 2005; Copenhagen University, 2022; IOP Publishing, 2013). It is only necessary speak to a scientist in a different field to experience that what feels like an entirely different language is being spoken. Tseitlin et al. likened these disciplines to cultures with a history of development, a plurality of approaches and viewpoints, and an uncertain and evolving future – just like cultures in our society. In its approach, science may be considered a dialogue between interacting discipline-cultures, analogous to the conglomeration of cultures that make up our modern world.

In each discipline-culture there exists a nucleus of core concepts and key paradigms which define the discipline, a body of working theories and daily applications of scientists, and a periphery of alternative ideas and viewpoints. An example of a concept in the nucleus is that of Quantum Superposition – the idea that no object has a definite state until it is measured, and rather exists as a superposition of many possible states. The body in the DC of quantum physics hosts concepts such as the qubit, the quantum equivalent to the binary digit with which computer calculations run.

Quantum physics is known mainly for having numerous interpretations. It is possible to count no less than sixteen (Cabello, 2017), many of which engage the public's fascination, such as the Many Worlds Interpretation and Quantum Darwinism. While most of these are not in regular working use by scientists in the laboratory, they certainly contribute perspectives to the discipline-culture, and thus can be considered part of the periphery.

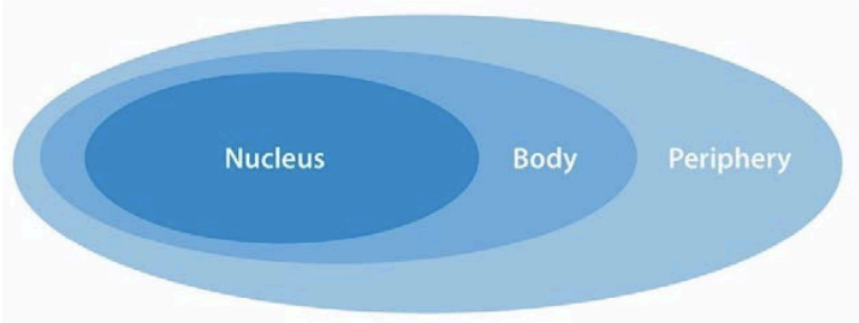


Figure 3: The discipline-culture framework as conceived and adapted by Tseitlin and Galili (2005)

Below we present the eight most important concepts for QT outreach as ranked by the participants of the Delphi study and placed in the discipline-culture framework of quantum physics. They are labelled by nucleus/body/periphery in Table 2. (See Seskir et al., 2023 for a full discussion of the implications of these results.)

Table 2: Top eight concepts/approaches to be utilised in QT outreach activities, rated in terms of their usefulness and adapted from Seskir et al., 2023

EU	Non-EU
Superposition (nucleus)	Superposition (nucleus)
Measurement (nucleus)	Measurement (nucleus)
Quantum state (nucleus)	Quantum state (nucleus)
Qubit (body)	Entanglement (nucleus)
Entanglement (nucleus)	Qubit (body)
Technological concepts (like quantum computers) (body)	Interference (body)
Interference (body)	Probability amplitude (nucleus)
Probability amplitude (nucleus)	Technological concepts (like quantum computers) (body)

The most striking result is that participants considered concepts in the nucleus of the DC (core principles of quantum physics) to be the most valuable for outreach. Those in the body of the DC (applications of core principles) were considered the next most important, and those in the periphery last. We believe this highlights an important disagreement in community opinion which must be addressed. The principles in the nucleus, while clearly valuable for inspiring the fascination of the public, are also highly prone to miscommunication and not necessarily representative of the daily experience of quantum technologists. Furthermore, we also believe there is also great value in activities in the periphery of the DC, which is supported by educational research and described in the next section. These results demonstrate the importance of clear guidelines being widely disseminated to practitioners.

Theoretical framework: Culturo-Scientific Storytelling (CSS)

Equipped with key concepts to include and problems to overcome in communicating QT, we may now consider with greater granularity how to structure outreach activities. An essential question to ask is: what outcome do we want from non-formal education? For what purpose do we communicate science? There are many benefits to doing so, such as raising awareness (Tarín-Pelló et al., 2022), preventing misinformation (La Bella et al., 2021), and inspiring future generations of scientists (Vennix et al., 2018). In this context, we are inspired by the work Five Minds for the Future by Howard Gardner (2008), in which he considers the minds required for the public to navigate and contribute to modern society. These minds must be disciplined, synthesising, creative, respectful, and ethical. We believe that public communication, with carefully crafted storytelling, may be contribute to the development of such minds.

In particular, Gardner's minds are inherently addressed in the everyday activities of scientists through the so-called inquiry cycle (Kuhn, 2011). Engaging in scientific thought is precisely the disciplinary thinking to which Gardner refers, and aspects of experimentation, conceptualisation, and theory-building related to such thinking develop synthesising and creative minds (Gardner, 2008). Scientists with an awareness of the need for responsible research and innovation (RRI) such as openness, inclusivity, and diversity, engage the ethical and respectful minds. Thus, promoting scientific thinking among the public through outreach may provide a great benefit in developing the skills needed to contribute to an ever-changing "society of acceleration" (Rosa, 2010). Goorney et al. (2022) collectively call these skills culturo-scientifc thinking, and believe they include elements such as disciplinary thought, creativity, and awareness of the fragility of scientific knowledge.

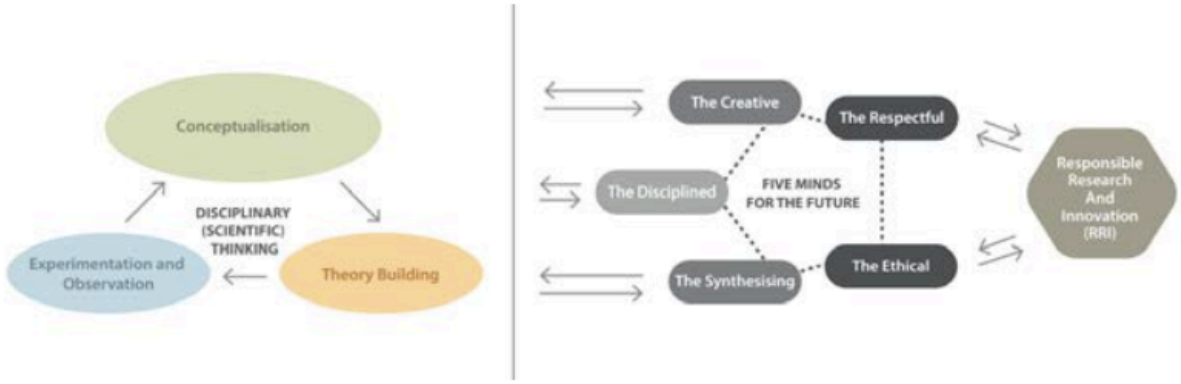


Figure 4: The approach taken by the QuTE4E pilot to develop Gardner's five minds through scientific thinking and RRI

CSS, the theoretical framework for a storytelling that best develops these skills, is summarised here (for more detail, see Goorney et al., 2022). While culturo-scientific storytelling was developed in and to promote QT, we note that it is a general framework for public communication of all areas of science and technology that are rapidly developing, such as Artificial Intelligence (He et al., 2019), cryptocurrency (Joo et al., 2019), and the Internet of Things (IoT) (Nižetić et al., 2020). We provide a summary of this method below for the use of educators.

First, we propose that activities be designed with the scientific inquiry cycle in mind. They should enable development of the disciplined, synthesising, and creating minds through application of experimentation, observation, conceptualisation, and theory building. Furthermore, we suggest that activities are designed with a sequential storytelling structure in which participants are taken on a journey through the field of QT. In order to structure this journey, we again make use of the discipline-culture framework as conceived by Tseitlin and Galili (2005).

Beginning in the periphery, where the most engaging and puzzling aspects of the field lie, is an effective hook and replicates the experience of a scientist encountering an idea that pushes the boundaries of their knowledge. Next, activities should be based around the nucleus, giving participants a paradigm through which to frame the subject. In QT, topics in the nucleus include the notion of superposition, and the wave-particle duality nature of light (Weissman et al., 2019). Appreciating whichever of these core principles are relevant enables activities based in the body

to be conducted, which consist of the applications of these ideas. For example, awareness of the superposition principle may enable explanation of quantum scenarios, such as interferometry and double-slit experiments.

Activities in the body allow participants to make predictions, test them, and build working theories in the scientific inquiry cycle. Finally, we suggest that finishing activities in the periphery is invaluable for developing culturo-scientific thinking skills. This gives participants exposure to the reality of the scientific experience – that no knowledge is ever complete, and the DC may grow and shift over time with new discoveries. These skills, including futures thinking (Levrini et al., 2021), epistemological awareness (Plakitsi & Kokkotas, 2010), and scientific thought (Chiofalo, 2022) are invaluable in the post-pandemic "society of acceleration" (Rosa, 2010) in which we currently live.

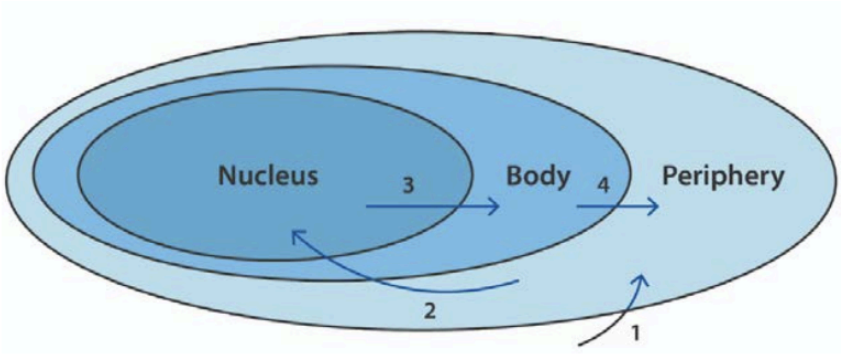


Figure 5: The culturo-scientific narrative approach explores the discipline-culture (a) in a journey reflective of the experiences of the scientist whereby each topic is addressed with scientific thinking, (b) in a journey constituted by an introduction with knowledge in the periphery (Arrow 1), later to be formalised into core principles in the nucleus (Arrow 2). Working applications can then be discussed and understood in the body (Arrow 3), before returning to the periphery to emphasise the evolving, incomplete nature of the DC (Arrow 4).

Participatory tools for storytelling

Implementing CSS requires that the participants be treated as scientists themselves. Yet how can this be accomplished when experimental QT setups require millions of euros to create? Addressing this need, members of the QuTE4E consortium and the wider community have developed and trialled a host of tools which can make implementing CSS practical. These toolboxes include resources which support experimentation, creativity, and formalisation. (For an extensive overview of this, see Seskir et al., 2022, p. 17). Here we show some examples of the tools developed within the pilot project, as a demonstration of the possible features of QT outreach activities designed with CSS.

Providing representational competence: The Quantum Odyssey

One major challenge for engaging scientific thinking in members of the public is being able to provide them with a foundation for understanding concepts in the nucleus and the body of the DC when they have no mathematical or scientific background. Let us consider the example of quantum gates and algorithms, the working basis (in the body of the DC) of quantum computation. An experienced physicist has a certain internal perception (or representation) of how gate operations work. This could be in the form of a visualisation, such as an arrow rotating around the Bloch Sphere, or a series of mathematical operations (Goorney et. al, 2023).

Visualisation software can be a powerful means to quickly provide participants the representational competence they need to understand a concept. In the case of Computation, the software Quantum Odyssey[119] is a self-paced learning platform which utilises a unique, fully visual method of displaying quantum gates and state vectors. Developed by Quarks Interactive through cross-disciplinary dialogue between physicists, computer scientists, educationalists, and industrial end-users, the software's aim is to tackle concerns in miscommunication about what quantum computers can do and offers a rigorous yet accessible learning space where learning how to create working code for universal quantum computers can take place.

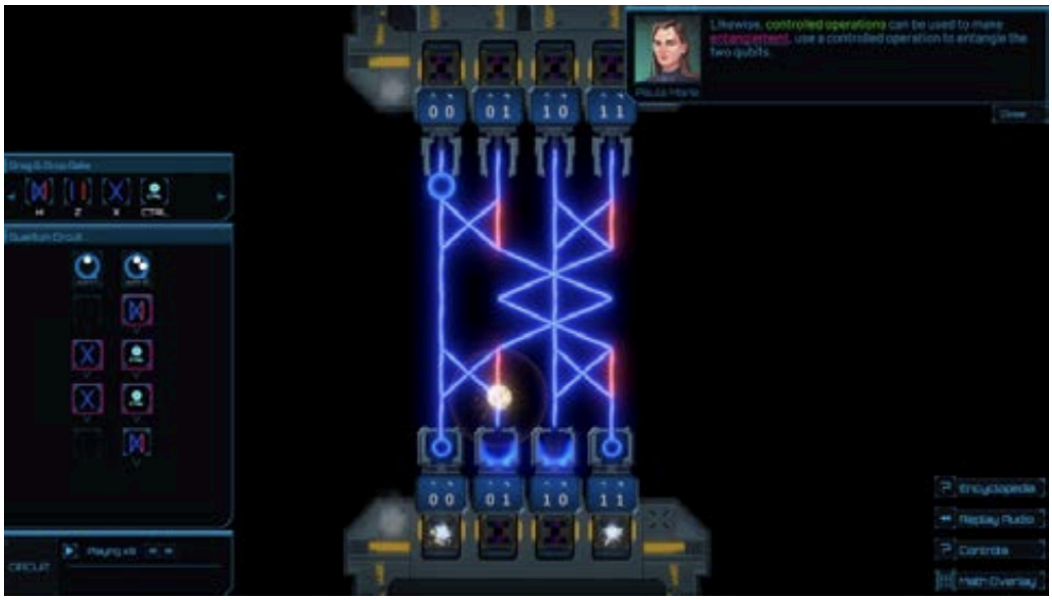


Figure 6: A snapshot from an introductory Quantum Odyssey learning puzzle. The circuit panel on the left and the Hilbert space of the circuit on the right are fully visualised. On the top right, the narration describes what is being observed. This representation of quantum gate operations is unique to Quantum Odyssey.

The software brings an original graphic version of the matrix-vector representation of the Hilbert spaces of full quantum systems. Because the translation for matrices to visual elements is exact, this representation is also exact. Indeed, advanced users can enter a "mathematics mode" and see the same operations in mathematical form. As a result, Quantum Odyssey can enable users to experience in an operational and participatory manner all of the fundamental

[119] Available on https://www.quarksinteractive.com/

principles behind quantum mechanics, including superposition, entanglement, and interference, and how to make use of them in constructing full proof-of-concept quantum algorithms. This means that members of the public can be guided with complete scientific accuracy through the nucleus and body of a storytelling version of quantum computation without any prior knowledge of gate operations or even fundamental principles of quantum mechanics.

Being a citizen scientist: Quantum Moves and Quantum Moves 2

Another challenge for outreach activities is providing an engaging “hook” for participants to engage with CSS. Why should they be interested in the activity? One possible solution to this is a class of tools in the field of citizen science (Roche et al., 2020), a model of conducting science in which members of the public are given the tools needed to participate in real research.

Quantum Moves (QM) and Quantum Moves 2 (QM2) are developed by ScienceAtHome based at Aarhus University (ScienceAtHome, 2012.) ScienceAtHome specialises in games and simulations in the field of citizen science (Roche et al., 2020), a model of conducting science in which members of the public are given the tools needed to participate in real research. Gamification of the tools with which the citizens interact encourages engagement and fosters participation. (Bowser et al., 2013) Thanks to the fun and intuitive nature of the games, QM and QM2 have been played over eight million times (ScienceAtHome, 2012).

In Quantum Moves, players take the role of a laser-based optical tweezer, guiding an ultra-cold atom through various challenges representing the operations of a quantum computer. The game-physics is a direct simulation of quantum mechanics, making use of the Schrodinger equation. The precise path taken through space is a class of experimental problems, known as quantum optimal control, with which physicists still grapple. Researchers using a computer algorithm to solve optimal control problems were able to demonstrate a benefit when using player-generated solutions as “seeds” over random seeding. Put simply, player solutions were able to help real researchers in a laboratory to build components of a quantum computer and conduct scientific research. Such a narrative is highly engaging for educators using the tool for outreach purposes and can provide a motivation for engaging with full CSS.

Navigating uncertain futures: The Quantum Decide Game

A final tool we would like to highlight is one that proved very popular among educators in the pilot project for its ability to engage individuals in the periphery of the DC, which is an essential component of CSS and invaluable in developing Gardner’s minds. QT is generally perceived as complex, difficult, and remote, and many do not grasp the potential benefits it will bring to society. The Quantum Decide Game (QDG), developed by the Spanish photonics institute ICFO (ICFO, 2021), aims to introduce member of the public to the field of QT and its implications through a participative activity that makes use of cards as discussion artefacts. An example of one such card is below in Figure 7:



Figure 7: An example of one of the thinking cards used by participants of the Quantum Decide Game in order to foster discussion about the possible implications of Quantum Technologies

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During QDG, the participants split into small groups (four to six people) that play the role of committees responsible for designing policies in research and innovation. Throughout the activity, they read, select, and discuss quantum concepts and technology, and explore cutting-edge scientific projects. The material provided underlines the importance of science and research in their lives with accessible examples. At the end of QDG, each committee reaches a strategic decision about the future of QT and shares it with the rest of the participants. The content of the cards varies from core concepts (nucleus), information about applications (body), and open discussions about issues with no clear solution (periphery), thus making it a powerful tool for implementing the CSS. Several examples of such discussions are provided in the next section. In addition, it promotes useful abilities for all citizens such as critical thinking and communication skills, and increased awareness about the current and future impact of QT on society at large.

Organising QDG for the public is simple and practical because it requires few resources. The cards that the participants use to gather information are freely available on ICFO outreach website (ICFO, 2021) in paper and digital format, and are translated into four different languages (Catalan, Spanish, English, and Italian). This makes QDG versatile and flexible, allowing it to fit into many different contexts and countries. ICFO and other institutions around Europe have used QDG to introduce quantum physics to high school students, secondary school teachers, and the general public. The simple setup makes it possible to organise it online and in person, and in many different settings (e.g. schools, museums, libraries, bars).

Feedback from participants emphasises the game's enjoyable and participatory nature, and that it allowed them to discover new concepts in an informal and engaging environment. In the Decide Game, people are not passive receivers of concepts as they are in classical outreach seminars, but are active characters that can choose information that is more relevant to them and interact with other participants to reach a consensus about what should be the future of QT.

Discussion: storytelling for the ethical and respectful

The tools described in Section IV are an effective means to engage individuals in the scientific thinking process, and thus develop the synthesising, creative, and disciplined minds of which Gardner conceived. We now discuss the implications of the CSS for reaching and developing the ethical and respectful minds through the promotion of Responsible Research and Innovation (RRI) (see Fig 4).

In February 2022, an RRI team at the University of Pisa ran a workshop for PhD students in both scientific and non-scientific disciplines as a transversal competence building activity (University of Pisa, 2022). Forty PhD students from a range of departments participated and were divided into twelve groups named after inspirational Quantum Physicists such as Marie Curie and Erwin Schroedinger. After an introduction to some of the historical development and core concepts of quantum mechanics through short accessible animations (QPlaylearn[120]), a keynote speech was delivered to tell the story about what quantum technologies are and where they are leading us. In this way, the discussion proceeded in the framework of CSS, from the periphery to the nucleus and the body of the discipline-culture. The primary activity for the groups was based around QDG, which was specialised to address the following questions: (i) what should be the priorities of QST scientific policies in order for them to be consistent with the RRI dimensions? and; (ii) how should the above priorities be ranked?

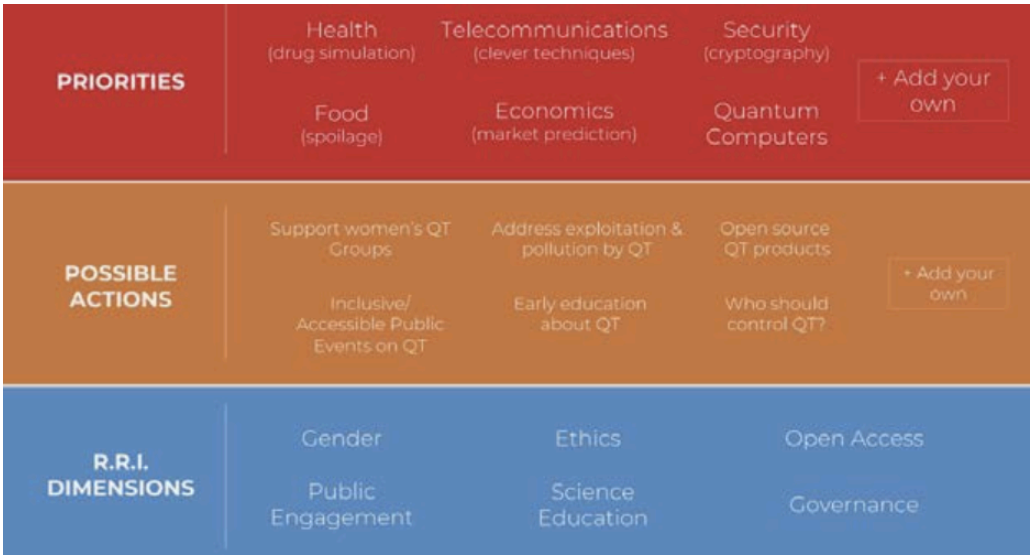


Figure 8: Guidance provided to participants of the RRI workshop based on QDG at the University of Pisa (2022)

The use of guided scientific inquiry (Furtak, 2006), where-by selected examples of possible implementations of the RRI dimensions in QT contexts were previously highlighted in the keynote, was a means of engaging the scientific thinking process of the participants (as highlighted in CSS, see Figure 4), even of those without any prior knowledge of the topic area. Participants were then provided with the Decision slide (see Figure 8) containing a basic set of

[120] Available on https://qplaylearn.com/education

priorities to be supported and/or changed at will. They then defined their choice of priorities, ranked them according to the RRI dimensions, and recorded the decision in a shared document according to a provided template. Finally, in the remaining half hour the different groups briefly reported their work in a plenary session. The final minutes were devoted to a discussion and question-and-answer session. The issues brought up here returned the participants to the periphery of the field, engaging with ideas and perspectives that are beyond what most scientists consider daily applications of QT.

In keeping with the spirit of RRI, training activities led to further collaborative design of a tool for developing RRI awareness and Gardner's respectful and ethical minds. The methodology used in these activities, which took place in the same PhD student workshop the following year, is inspired by "staff-student co-creation" in which learners and teachers together generate educational content for future learners. Because learners are engaged in the process of developing educational material with staff, "learning by doing", this method has been shown to yield benefits in engagement, awareness, and enhancement of learning (Cook-Sather, 2014), Through the duration of the didactic path described above, participant groups were prompted to highlight key stories and info cards that raise important questions they might use to educate the public about the principles of RRI. Several examples of resulting discussions are shown below, and the key cards from QDG which prompted them are available in the Appendix (Figures A1–A5):

i) Is scientific funding into the "mysteries" of quantum mechanics a wise investment for society? Is it worth investing significant resources into potential applications that might benefit society only in the longterm? (Figure A1)

ii) We are already using some of the unusual properties of quantum mechanics as the founding principles of widespread common technologies, i.e. lasers, solar panels, etc. (Figure A2).

iii) We can use quantum mechanics to generate new technologies that will impact society in many different fields. It should therefore be considered a responsible investment for governments worldwide (Figure A3).

iv) Many principles of quantum physics contradict common sense. Is this a limitation of the validity of this theory? Should the public trust such a "weird" theory (Figure A4)?

v) Because most members of the public are not educated to "speak the language" of quantum physics, news outlets often generate misinformation. If this misinformation makes its way to policymakers and investors, it can do serious damage to the adoption of QT in society, which may cause us to miss out on many of the future benefits of QT, for example in healthcare and environmental safeguarding (Figure A5).

Typically, one of the difficulties of making the public aware of issues related to RRI is the lack of contextuality. Dimensions such as "open access" and "ethics" can seem distant and disconnected from everyday life without a field in which to ground them, and can thus be difficult to convey in both formal and informal contexts (Margherita & Bernd, 2018).

The QDG allows these issues to be contextualised by QT and carefully explained through story, thinking, and information cards, encouraging participants to develop the respectful and ethical minds in the process.

Conclusion

A key ongoing theme in the findings from the QuTE4E Pilot is the value of an engaging narrative in outreach efforts in order to develop the skills people need to navigate the uncertain futures brought on by the advent of modern technologies. Participatory, hands-on tools are a key to implementing CSS, and the recent work of the scientific community in this area is now extensive. The majority of concepts we consider important to communicate to the public (shown in Table 2) are accessible through the demonstration of games and interactive tools (Seskir et al., 2022). Over the duration of the pilot project, these tools and CSS were implemented in many small-scale events intended to expose the general public to the wonders of QT, such as hackathons (Quantum AI Foundation, 2022) and game jams (Internet Festival, 2021). As governments become more aware of the negative implications of public misunderstandings of new technology, QT outreach is increasingly becoming a major part of international strategies for developing the field. Overhype (Sartori & Theodorou, 2022), misinformation (La Bella et al., 2021), and widespread misunderstanding (Dignam, 2020) are several recent examples from the field of AI, which is currently undergoing a public explosion of interest.

Europe Day, held in the headquarters of the European Commission in Brussels, was a particularly large initiative (European Union, 2022). QuTE4E ran the booth representing the research and development efforts of QT in Europe, the Quantum Flagship[121]. An estimated fifteen thousand members of the general public passed through the venue where Quantum Moves 2 and Quantum Odyssey were set up and used in a participatory manner to engage members of the public directly into the periphery of the DC, and offer a discussion around the implications of the technologies they demonstrate.

In Italy, the project Italian Quantum Weeks[122] was the first national effort of its scale, intended to raise awareness of QT and help members of the public make sense of the quantum news they may have encountered on the web, in newspapers, or elsewhere. IQWs has now run over two consecutive years, and involved more than one-hundred and thirty researchers, technicians, communicators, and teachers from over forty research institutes across seventeen Italian cities.

And finally, UNESCO is currently in the planning stages for the dedication of 2025 as the International Year of Quantum Science and Technology. This prospect is representative of the degree to which QT development will impact society, and yet it is currently significantly underknown and misunderstood by members of the public. With increasing attention drawn to QT on an international scale, it is crucial that the opportunity to communicate the field is not wasted, and that every outreach scenario is conducted as effectively as possible. The risks of drawing attention to QT, without careful thought to how to do so, are substantial (Sartori &

[121] Available on https://qt.eu/
[122] Available on http://www.quantumweeks.it

Theodorou, 2022; La Bella et al., 2021; Dignam, 2020). QT may avoid such issues by developing large scale outreach efforts, but only if they are accompanied by research-based guidelines. We highlight that the development of such guidelines, which we call Physics Outreach Research (POR), is crucial in the current “society of acceleration” (Rosa, 2010) where technological advancements are driving rapid sociocultural reform. Such a perspective must also be adopted in other emerging fields such as cybersecurity, and particularly Artificial Intelligence. These fields may benefit from a community-based approach as the QuTE4E pilot project has used in QT.

The result of this community has been CSS (Goorney et al., 2022), and the many tools available for implementing it (Seskir et. al, 2022). In this paper, we have offered several examples of their application, and how they may develop in members of the public the disciplined, synthesising, creative, respectful, and ethical minds they need to navigate the uncertain future of a society rapidly changed by technology.

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Appendix

Quantum Decide Game discussion cards used in RRI workshop:

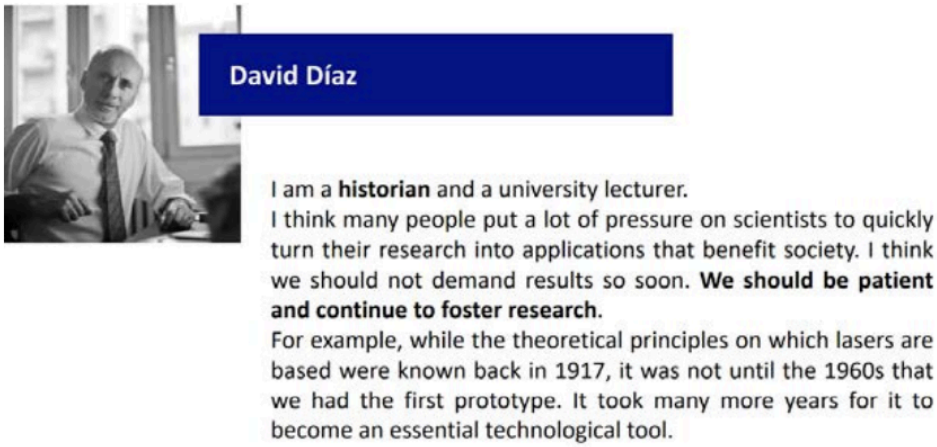


Figure A1: Is scientific funding to explore the "mysteries" of quantum mechanics a wise investment for society? Is it worthy to invest significant resources for the possibilities of application that might benefit society, but only in the long term?

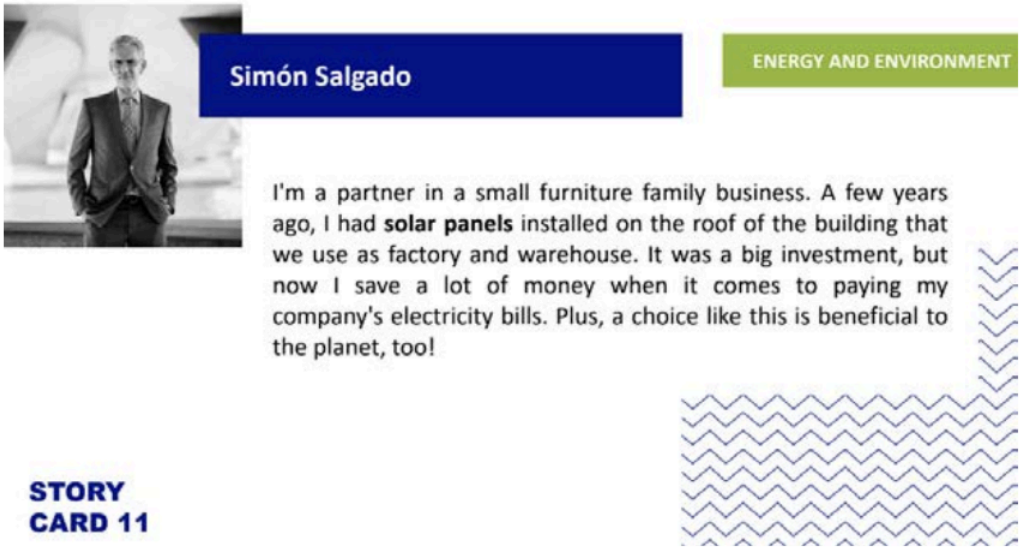


Figure A2: We are already using the bizarre properties of quantum mechanics as the founding principles of widespread common technologies, i.e. lasers, solar panels, etc.

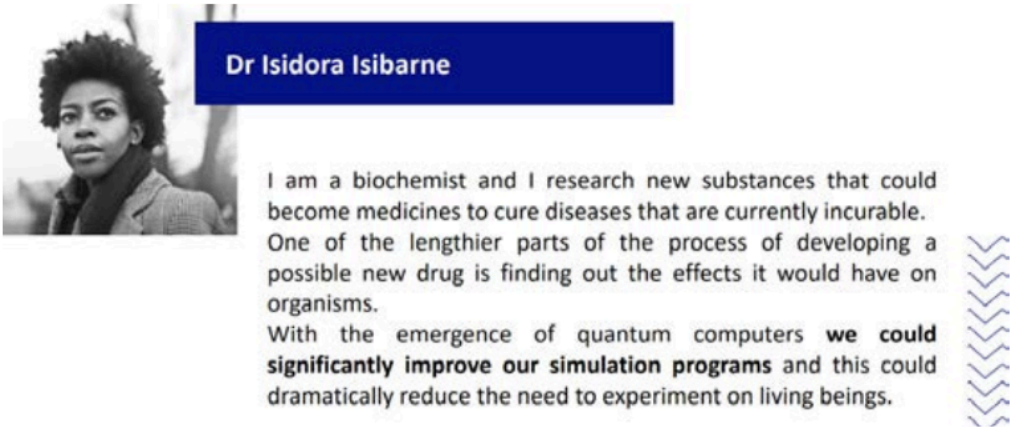


Figure A3: We can use quantum mechanics to generate new technologies that will impact society in many different fields. It should therefore be considered a responsible investment for governments worldwide.

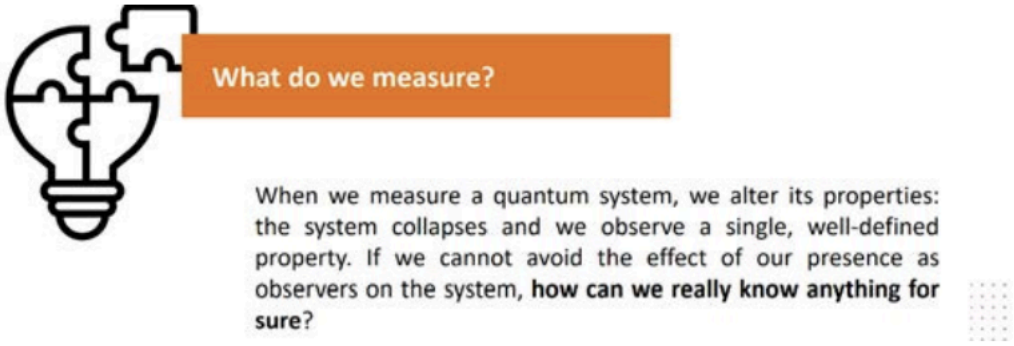


Figure A4: Many principles of quantum physics contradict common sense: is this a limitation to the validity of this theory? Should the public trust such a “weird” theory?

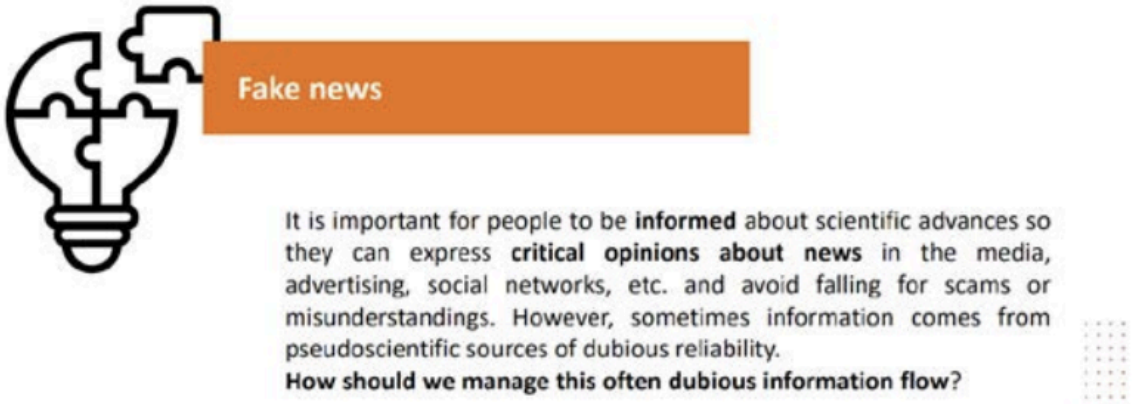


Figure A5: Because most citizens of the public are not educated to “speak the language” of Quantum Physics, news outlets can be prone to generating misinformation. If this makes its way to policymakers and investors, it may do serious damage to adoption of QT in society, which may cause us to miss out on many of the future benefits of QT, such as in healthcare and environmental safeguarding.

Conference Proceeding 1.11: Exploring Pitfalls for Defence and Security by Narratives on Quantum Technologies[123]

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ABSTRACT

Quantum technologies have clear potential for defence and security applications. However, the development of these applications can be hindered by pitfalls that can come with narratives about how we see quantum technologies. In this work, we build upon a previous exploration of how three common narratives hinder the democratization of quantum technologies. In this paper, we present these three narratives and discuss the pitfalls they cause for developing and applying quantum technologies for defence and security.

For the narrative of quantum computing as a threat, we examine the phenomenon of threat inflation, which exaggerates the potential risks of quantum computers and can create a sense of urgency that is not necessarily warranted and may lead to rushed or poorly considered policy decisions. For the narrative of quantum mechanics as incomprehensible, we discuss how this leads to decision-makers often offloading their responsibility by claiming they cannot understand quantum mechanics, leading to the pitfall that these decision-makers do not have meaningful engagement with experts in the field. For the narrative of quantum technologies as an arena for geopolitics, we explore the pitfall of prematurely closing down potential constructive international collaboration due to overprotectionism.

Our work emphasizes the importance of critically examining the three narratives and adopting a more nuanced approach to discussing quantum technologies. By doing so, we aim to empower decision-makers and researchers in defence and security to arrive at a more even and realistic assessment of the potential and threats of quantum technologies for defence and security.

Keywords: quantum technologies, geopolitics, narratives, democratization

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123 https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/Forms/Meeting%20Proceedings%20Document%20Set/docsethomepage.aspx?ID=46238&FolderCTID=0x0120D5200078F9E87043356C409A0D30823AFA16F602008CF184CAB7588E468F5E9FA364E05BA5&List=7e2cc123-6186-4c30-8082-1ba072228ca7&RootFolder=https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-IST-SET-198 or https://publikationen.bibliothek.kit.edu/1000171675

1. Introduction

With their transformative potential, Quantum Technologies (QT) have garnered significant attention in recent years, especially in defence and security. The promise of quantum computing, quantum communication/cryptography, and quantum sensing have led to what some have dubbed a “quantum gold rush” [1], with a surge in investments and research aiming to harness these technologies’ advantages. However, the discourse surrounding QT is filled with narratives that can shape perceptions, influence decisions, and determine their development and application trajectory. While some of these narratives are rooted in genuine concerns, others can be misleading or overly simplistic, leading to pitfalls in applying QT in defence and security.

Narratives are crucial in shaping the public’s and policymakers’ understanding of complex scientific and technological advancements. We focus on three dominant narratives related to the democratization of QT [2]: the portrayal of quantum computing as an imminent threat, the belief that quantum mechanics is inherently incomprehensible, and the framing of QT as a new battleground for geopolitical dominance. Each narrative offers a unique perspective on the quantum landscape but also brings potential pitfalls. Understanding these narratives is essential, not to discard them, but to ensure they are grounded in reality and advance QT responsibly for societal betterment and security.

Given the global implications of these narratives, especially in the context of defence and security, their relevance extends to international alliances such as NATO. Article 2 of the North Atlantic Treaty emphasizes the development of peaceful and friendly international relations and the strengthening of free institutions. As NATO STO focuses on generating and applying state-of-the-art knowledge for defence and security in our increasingly complex sociotechnical societies, the interplay between democracy, technology, and value contexts emerges as a central concern. Different value contexts, whether they view democracy as an instrumental or intrinsic value, can shape the way narratives are constructed, interpreted, and acted upon. In a recent paper we delved [2] into the aforementioned narratives concerning the democratization of QT, exploring their implications under different theories of democracy and the underlying value contexts that influence them. In this study we highlight potential pitfalls associated with these narratives and emphasize the need for a nuanced discourse on QT. By critically examining these narratives, we hope to foster a balanced understanding that aids decision-makers and researchers in defence and security in making informed choices about QT’s trajectory.

1.1 Theories of Democracy and Value Contexts for Democratization

The democratization of technology is a complex concept influenced by different theories of democracy: deliberative, participatory, and representative. Deliberative democracy advocates for informed discussion among stakeholders before making technological decisions, ensuring collective reasoning. Participatory democracy emphasizes direct public involvement in shaping technology, aligning it with the broader public interest. Representative democracy, on the other hand, relies on elected officials to make informed technological decisions on behalf of the public, ideally after consulting experts and considering public opinion.

Balancing public participation in technology, especially in sensitive areas like defence and security, is challenging but crucial for upholding democratic values like transparency and broad

participation. While it may be practical for for-profit organizations to treat democracy as an instrumental value, public and international organizations should aim to adopt democracy as an intrinsic value. This nuanced approach strengthens democratic institutions and ensures that various stakeholders have access to advancements in science and technology.

While the democratization of QT is a subject of study in itself, it is also closely linked to the practical implications these technologies have in the realm of defence and security. The narratives that shape our understanding of QT's democratization can also give rise to specific pitfalls that have real-world consequences for policy and security measures. For instance, the narrative that portrays quantum computing as an imminent threat can lead to 'threat inflation,' affecting not just public perception but also policy decisions in defence. Similarly, the narrative that quantum mechanics is 'incomprehensible' can result in decision-makers abdicating their responsibilities, leading to gaps in policy and oversight. Finally, narrative of QT as the arena for geopolitics can lead to unnecessary overprotectionist actions which have considerable associated costs in terms of missed opportunities for the positive outcomes of collaboration between different national actors. In the following section, we delve deeper into these pitfalls, examining how they arise from prevailing narratives and provide historical examples to discuss what they mean for stakeholders in defence and security.

2. Narratives and Pitfalls

This section outlines the three previously identified narratives concerning QT and their impact on democratization. We also highlight potential pitfalls these narratives may pose for defence and security stakeholders. It's essential to recognize that the narratives discussed aren't exhaustive, nor are the pitfalls the sole consequences of these narratives. Narratives inherently present a mix of opportunities and risks shaped by their foundational arguments and contexts. What one stakeholder perceives as an opportunity might be seen as a risk by another, and these perceptions can vary based on time and context.

Consequently, narrative interpretations can differ among stakeholders. Our focus here is to illustrate how narratives that impede democratization can also present challenges for defence and security by creating pitfalls. The analysis underscores the importance of critically evaluating narratives for potential pitfalls when endorsing or promoting them.

The three narratives previously formulated are (i) Quantum Computing as a Threat, (ii) Quantum Mechanics as Incomprehensible, and (iii) QT as an Arena for Geopolitics. Quantum computing is often portrayed as a looming cybersecurity threat with the potential to break most encryption types. While the actual risk may be distant, the first narrative fuels policies which employ disproportionate actions and prioritizes security concerns over broader technological development and access. The belief that quantum mechanics is too complex for even experts to understand has limited broader engagement and inadvertently bolstered pseudoscientific claims. The second narrative restricts QT development to a niche group, hindering democratization and public discourse on its implications. QT is increasingly viewed as a geopolitical battleground, especially between major powers like the US and China. While emphasizing national security, the third narrative limits international collaboration, diverts research priorities, and hinders broader collaborative efforts in the QT domain.

2.1 Pitfalls for Defence and Security by Narratives

The first pitfall concerns the distortion of quantum computing's genuine risks due to threat inflation, which can precipitate premature and misguided policy decisions fuelled by undue urgency. The term "threat inflation" gained traction in the mid-2000s through international relations literature, with scholars like Chaim Kaufmann examining the Iraq War and democratic decision-making [3]. The portrayal of quantum computing as a significant threat to our digital infrastructure can amplify this inflationary threat perspective. This often blurs the distinction between the potential risks quantum computers pose to critical defence and security infrastructure and civilian digital systems, such as banking or smart-home platforms. This ambiguity sometimes prompts extreme viewpoints like "Should We Build Quantum Computers at All?" [4] in popular scientific discourse. Moreover, it may sway decision-makers towards endorsing cybersecurity policies that don't accurately reflect the actual threat landscape.

The second pitfall stems from the narrative that quantum mechanics is incomprehensible, allowing decision- makers to shift responsibility to select experts, thereby sidestepping meaningful engagement with the field. This often results in decision-makers having a limited grasp of the field's intricacies and a hesitancy to delve deeper. Given the complexity of QT, which encompasses diverse technologies like quantum computing, sensing, and communication, and is supported by a myriad of complementary technologies such as cryogenics, control electronics, and photonics, it's crucial to understand the 'quantum' essence across these varied domains. However, faced with this daunting task, many decision-makers might resort to saying, "I wouldn't understand even if I tried." While this may seem like a nod to the experts' proficiency, it ultimately allows decision-makers to distance themselves from the subject.

The final pitfall we introduce here arises from the narrative framing QT as a geopolitical battleground, which risks prematurely curtailing valuable international collaborations due to heightened protectionism. The North Atlantic Treaty's Article 3 emphasizes the importance of both individual and collective efforts to bolster defence against armed attacks. This creates a nuanced challenge: determining collaboration partners for QT's defence and security applications while preparing for QT's commercial era. Both the EU and the US have initiated protective measures, with the EU enforcing investment screening and export controls, and the US's DoD expanding technology protection plans under the NQIA to encompass early research phases. Balancing values like security and prosperity, which can sometimes clash, necessitates a comprehensive understanding of technology development policy decisions. Given the rising emphasis on technology sovereignty among NATO members, the geopolitical narrative surrounding QT demands careful management to harmonize the obligations of Article 3 with individual national policies.

2.2 Historical Contexts for Pitfalls

To contextualize these pitfalls, historical examples offer valuable insights. The first pitfall, related to threat inflation, can be exemplified by the "missile gap" narrative that John F. Kennedy, a US senator back then, propagated in the late 1950s. This narrative led to policy decisions based on inflated perceptions of threat rather than accurate intelligence, thereby skewing defence priorities. Another example for this pitfall is the millennium bug or the year 2000 problem, where

an inflated expectation of potential harm caused overpreparation which ended up costing somewhere between $40 billion and $300 billion [5], [6] which in inflation adjusted terms correspond to over $50 billion to $500 billion.

The second pitfall, concerning the abdication of responsibility due to the perceived incomprehensibility of quantum mechanics, finds a parallel in the era known as the “Crypto Wars.” During this period, stringent export controls were imposed on cryptographic algorithms, largely due to policymakers’ limited understanding of the technology. This led to policy goals that were not only unattainable but also counterproductive. In the end, the policies had to be abandoned as they envisioned cryptographic algorithms similar to military equipment, which effectively made implementation of such export control policies rather difficult. The end of “Crypto Wars” era also led to a better understanding of cryptography and the paradigm that is usually referred to as zero trust architecture today.

The third pitfall, which involves the risk of prematurely ending international collaborations due to geopolitical narratives, is illustrated by the space race between the US and the USSR. This competition consumed vast resources and overshadowed potential areas for cooperation. However, the Apollo-Soyuz Test Project of 1975 demonstrated that such competition was not the only path; meaningful collaboration was possible and beneficial for both parties. There are opposing views on the topic, however, it might be argued that the space race narrative postponed the signing of the Outer Space treaty (signed 1967), which paved the way for peaceful collaboration in space missions.

These historical examples serve to underline the real-world consequences of succumbing to misleading narratives, emphasizing the need for a nuanced understanding when shaping policies related to defence and security in the realm of QT. As illustrated by the pitfalls and examples above, the interconnections between narratives naturally extend to the pitfalls they engender. Both experts and significant entities, such as NATO STO, play dual roles in both propagating and challenging prevailing narratives. A reflective examination of which narratives to endorse and how to position oneself in relation to them is crucial to sidestep the potential pitfalls and risks they introduce.

3. Conclusion

The narratives surrounding QT play a pivotal role in shaping their development, application, and perception, particularly within the defence and security sectors. In this paper, we investigated the potential pitfalls arising from three dominant narratives: the portrayal of quantum computing as an imminent threat, the perception of quantum mechanics as inherently incomprehensible, and the framing of QT as a geopolitical arena. While these narratives stem from genuine concerns, they can inadvertently introduce pitfalls, such as threat inflation, decision-maker detachment, and the premature curtailment of international collaboration. These pitfalls can not only misguide policy decisions but also obstruct the broader democratization and development of QT.

Understanding these narratives is essential, not to discard them, but to ensure they are grounded in reality and advance QT responsibly for societal betterment and security. For stakeholders in defence and security, especially within the NATO alliance, a critical evaluation of

these narratives is paramount. This ensures that QT's development and deployment align with both defence priorities and broader societal goals, all while considering the underlying value contexts that influence their interpretation and action. As the QT landscape continues to evolve, it is incumbent upon decision-makers, researchers, and other major stakeholders to navigate these narratives with discernment and responsibility. By doing so, we can harness QT's potential in a manner that ensures policies and decisions resonate with the actual landscape of QT, strengthening free institutions, and fostering peace and prosperity for all those committed to QT's development.

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Article 2.1: Democratization of quantum technologies[124]

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Keywords: *democratization, quantum technologies, quantum computing, theories of democracy*

Abstract

As quantum technologies (QT) advance, their potential impact on and relation with society has been developing into an important issue for exploration. In this paper, we investigate the topic of democratization in the context of QT, particularly quantum computing. The paper contains three main sections. First, we briefly introduce different theories of democracy (participatory, representative, and deliberative) and how the concept of democratization can be formulated with respect to whether democracy is taken as an intrinsic or instrumental value. Second, we give an overview of how the concept of democratization is used in the QT field. Democratization is mainly adopted by companies working on quantum computing and used in a very narrow understanding of the concept. Third, we explore various narratives and counter-narratives concerning democratization in QT. Finally, we explore the general efforts of democratization in QT such as different forms of access, formation of grassroot communities and special interest groups, the emerging culture of manifesto writing, and how these can be located within the different theories of democracy. In conclusion, we argue that although the ongoing efforts in the democratization of QT are necessary steps towards the democratization of this set of emerging technologies, they should not be accepted as sufficient to argue that QT is a democratized field. We argue that more reflexivity and responsiveness regarding the narratives and actions adopted by the actors in the QT field and making the underlying assumptions of ongoing efforts on democratization of QT explicit, can result in a better technology for society.

1.Introduction

Over the course of the last several decades, the impacts of transformative technologies have been the subject of intense scholarly and public debate and scrutiny. Much of this focus has been on emerging technologies such as artificial intelligence, nanotechnology, and biotechnology. Similarly, it has long been the contention of science and technology studies (STS) and the social studies of science that transformative technologies, given their vast and pervasive impacts on society, should be framed and shaped by, designed for, and deployed to support democracy (Foladori and Invernizzi 2008, Montes and Goertzel 2019, Beumer 2021). Recent developments in the field of quantum technologies (QT), particularly quantum

[124] https://iopscience.iop.org/article/10.1088/2058-9565/acb6ae

computing, provide strong reasons to attend to the impacts of that technology also (Coenen and Grunwald 2017, Vermaas 2017, Coenen *et al* 2022), which is the topic we take up in this paper.
QT are a set of emerging technologies reliant on the utilization of quantum phenomena and separated in different fields such as sensing, communications, simulation, and computation (de Touzalin *et al* 2016). This process of emergence is commonly referred to as *the second quantum revolution* (Dowling and Milburn 2003) to historically distinguish it from *the first quantum revolution*, which yielded technological artefacts such as transistors, medical imaging devices (like magnetic resonance imaging (MRI)), and lasers. These previous devices created the backbone of technical capabilities which allowed the flourishing of the information and communication technologies (ICT) sector, and yielded products (such as computers and smartphones) that fundamentally altered how several aspects of society function. Though semiconductors used for transistors, and optical elements used for lasers require understanding of quantum mechanics, they do not embody or exploit certain quantum phenomena such as entanglement. Recent developments in technical fields such as nanotechnology, quantum optics, and condensed matter physics resulted in capabilities that allow researchers to reliably create, manipulate, and exploit quantum specific phenomena at a high precision and accuracy levels that were previously not possible. This enabled further research and development efforts that supported *the second quantum revolution*.

The extent of this technological revolution can be observed quantitatively. The number of academic articles, patents granted, and start-ups founded focused on QT has been increasing rapidly in the last decade (Seskir and Aydinoglu 2021, Seskir and Willoughby 2022b, Seskir *et al* 2022a). As of early 2022, there is nearly 30B Euro of committed or promised public funds for QT until 2030 in terms of national initiatives (QURECA 2022). In comparison, the literature on 'social' aspects of QT is limited to only two-digit numbers (Wolbring 2022). Some experts in the field expect that QT could lead to a more unequal distribution of power and wealth between those who are already operating at a very high level technologically and those who do not (de Wolf 2017, pp 274–5, DiVincenzo 2017, p 248).

Considering this risk, the rapid increase in the academic and commercial landscapes, the relative lack of the literature on the societal aspects of these technologies, and the lagging of public communication and discussion on QT behind the rapidly increasing public and private funding, we argue that a closer examination on how the notion of democratization is being used, and how democratization may work in the field, is necessary.

The democratization of technologies seems to be beneficial *prima facie*, but is however far more complex. There are various schools of thought underlying the meaning and mechanics of what it means to democratize technology, each bringing with them both philosophical as well as technical challenges (Tringham and Lopez 2001, Bijker 2010, Verbeek 2013). In any case, the expertise necessary to innovate in any given technical domain usually accrues in the hands of small groups of experts, thus resisting the basic tenets of democratic politics where all should equally contribute in principle. Still, the huge impacts of transformative technologies demand that how they are designed and deployed incorporate democratic deliberation to achieve more acceptable political decision making.

This paper aims to make a start with filling this lacuna by considering different theories of democracy (participatory, representative, and deliberative), and how the concept of democratization can be formulated with respect to these theories under the postulation of democracy as an intrinsic or instrumental value, without going into broader discussions of ethical or other philosophical aspects. These understandings of democratization are then used to frame how the various actors within the QT community appropriate and use the language of democratization. This is followed by an exploration and analysis of narratives, counter-narratives, and actions concerning the democratization of QT. We focus in our discussions on mainly quantum computing. In the conclusion section, we argue that although the ongoing efforts in the democratization of QT are necessary steps, they should not be accepted as sufficient to say that QT is a democratized field. We argue that more reflexivity and responsiveness regarding the narratives and actions adopted by the actors in the QT field, and making the underlying assumptions of ongoing efforts on democratization of QT explicit, can result in a better technology for society.

2.Modalities of democratization

The notion of democratization in innovation and technology development can be situated in the vast literature concerning the democratization of science in knowledge societies (Domènech 2017). The issue of how to incorporate democratic deliberative processes into what are expert domains of knowledge has been a longstanding issue in STS with no clear-cut or widely agreed-upon solutions. This has led to a large number of contributions that raise the question of how democratic systems can still function in increasingly complex knowledge societies (Callon *et al* 2001, Grunwald *et al* 2006, Marres 2007) particularly given that the rationales regularly given by science managers in public deliberative spaces often distill down to opaque and complex quantitative models of democracy (Tickner and Wright 2003).

As a potential solution, scholars have proposed that expertise itself serves as the ideal locus for democratization, opening up the possibilities for laypeople to gain expertise and have a better say in our knowledge societies (Lascoumes 2002). Still, as Miquel Domènech aptly states, such an enterprise even if 'taken seriously does not mean it is an easy or even possible task' (Domènech 2017, p 127). This, therefore, further raises concerns regarding the logical compatibility between democratic processes and expertise *per se* (Liberatore and Funtowicz 2003, Domènech 2017). These concerns are perhaps even more important in the case of QT, as their relevance and functioning are often more difficult to explain to non-scientists than other technologies.

Various approaches have been proposed and used to democratize science and technology governance in knowledge societies, mostly via programs of stakeholder and citizen participation. This is often understood as the various means by which stakeholders can be involved in the policy cycle which includes:

(a) identifying policy priorities
(b) drafting the actual policy document,
(c) policy implementation; and
(d) monitoring implementation and evaluation of the policy's impacts (OECD 2020)

Stakeholders are defined differently across the literature. The OECD (2020) defines stakeholders as:

> any interested and/or affected party, including: individuals, regardless of their age, gender, sexual orientation, religious and political affiliations; and institutions and organizations, whether governmental or non-governmental, from civil society, academia, the media or the private sector (OECD 2020).

Still, there are longstanding and more generalized conceptions of stakeholders within the realm of participatory and value-sensitive design, the latter of which makes a distinction between two classes of stakeholders, i.e. direct and indirect stakeholders:

2.1 Direct stakeholders

An individual or group who interacts directly with a technology. For example, a system of electronic medical records might be designed for doctors and insurance companies (Friedman *et al* 2017, Friedman and Hendry 2019).

2.2 Indirect stakeholders

An individual or group who is impacted by a technology but does not directly interact with it. For example, many electronic medical systems are intentionally designed to be used exclusively by doctors and, depending on the country, by insurance agencies. This, naturally, will impact patients (Friedman *et al* 2017). Another example is when a small drone flies over a bystander, they may be bothered by its sound and presence and their privacy might be violated. In this case, the bystander would be an indirect stakeholder and the operator of the drone would be a direct stakeholder (Vernim *et al* 2022).

Still, regardless of the definition(s) used for the stakeholder populations chosen to be elicited, the functionally significant point is that stakeholder groups are identified and given consideration in information, consultation, and engagement processes. Particularly given their role concerning the creation and delivery of policy decisions guiding science and technology innovation rather than in the direct day-to-day technical work of experts.

Although often used interchangeably, *deliberative* and *participatory* democracy have unique elements despite sharing many commonalities. The distinction is important not only for QT designers but for policymakers as well. There is a third conception of democracy, less referred to within the realm of science and technology policy but in general still more relevant than the other two, and that is *representative* democracy.

The number of participants that are included, the type(s) of participation, as well as the method used to select participants differ between deliberative, participatory, and representative democracy theories. For one way of distinguishing them, see table 1:

In their Gastil and Levine (2005), Gastil and Levine define deliberative democracy as that which ‘strengthens citizen voices in governance by including people of all races, classes, ages and geographies in deliberations that directly affect public decisions.’ A basic idea is that political decision-making processes become more rational and their results more acceptable through the

involvement of well-informed citizens and stakeholders in deliberation. This approach to the democratization of science became popular in academic literature during the 1980s with authors like Habermas (1981) and Mansbridge (1980).

Table 1. Key differences between deliberative, participatory, and representative democracy. Source: OECD (2020), based on descriptions in Carson and Elstub (2019) [modified].

	Number of participants	Type of participation	Participant selection method
Deliberative democracy	Relatively small (but representative) groups of people per activity. The aim is to have deep deliberation, which is difficult to achieve with a large number of people.	Deliberation requires that participants are well-informed about a topic and consider different perspectives in order to arrive at a public judgment (not opinion) about 'what can we strongly agree on.'	Ideally, a civic lottery, which combines random selection with stratification, to assemble a public body that is: representative of the public, able to consider perspectives, and not vulnerable to being stacked by representatives of powerful interest groups.
Participatory democracy	Large numbers of people, ideally everyone affected by a particular decision. The aim is to achieve breadth.	**More participation**, in all aspects of politics, from all citizens who choose to be involved; an embrace and encouragement of a **diversity** of opportunities for political engagement.	Self-selected participation in order to enable as many people as possible to share the experience.
Representative democracy	Large numbers of people, ideally everyone affected by a particular decision. The aim is to achieve majority representation.	**Representation** requires representative candidates to be chosen and approved by constituent populations as the voice for their values and concerns.	Selected candidate participation determined by the total number of participants as representatives of their values and concerns.

Participatory democracy, on the other hand, has its roots in the civil rights movements that characterized the 1960s (Pateman 1970). The motivation behind this form of democracy was the demand by citizens, particularly by unrepresented groups, to have greater influence in public decision making processes. Participatory democracy differs from deliberative democracy in that its emphasis is not primarily on how citizens can influence established, usually representative decision making processes from the outside, but on how institutions can augment citizens' abilities and capacities to participate in decision making and make such participation more meaningful (Pateman 2012).

In representative democracy in the traditional sense, i.e. before the deliberative and participatory turns, deliberation was mostly non-public and limited to elected representatives, invited experts, and rather small numbers of interest groups as only involved stakeholders. However, this constellation is not typical of most political discourse on science, technology and innovation. Participants in this discourse tend to have less clear roles than participants in the core processes of representative democracy (e.g. in parliament) and may be (even) less representative of society in general and of affected populations in particular than in other policy areas—which is an argument for including more deliberative and participatory mechanisms in the system. (Grunwald *et al* 2006, Brown 2009, Disch 2009).

Table 2. Modalities of applied democratization in innovation.

Front end	Back end
Access to education Funding allocation	Open access publications Accountability

In science policy, two major loci for democratization pathways can be distinguished (see table 2), one on the front end (access to education; science funding) and one on the back end (open access publishing; accountability). On the front end, opening up access to education can strengthen democratic knowledge societies. Likewise, democratic (and in particular deliberative and participatory) decision making concerning where funding is allocated can permit a form of public democratic engagement of what spheres of innovation should receive attention. On the back end, open access publication available without costs to readers (despite the epistemic hurdles in comprehension) is a key endeavor currently being undertaken (see Else 2021).

Accountability, however, remains a more nebulous and abstract modality for democratization in innovation. Within the responsible research and innovation literature, scholars have noted that innovation spheres have mostly remained separated from citizen engagement (Stahl *et al* 2021). Owen *et al* (2021) argue that this separation is the consequence of innovation spheres not sufficiently aiming to be a 'site for politics', i.e. a domain where deliberation, continuous debate, negotiation, and discussion concerning how innovation should be governed as well as what goals innovation should be driving towards.

The concept of accountability is dealt with in a substantial corpus in the philosophical literature concerning technology. Accountability has traditionally been described as a retrospective, backwards-looking form of responsibility (i.e. van de Poel 2011) or as a passive form of responsibility, more specifically as after-the-fact evaluation demanding justification which, consequently, provides the foundations for assigning blameworthiness (Pesch 2015). However, recently scholars have interpreted accountability such that it could have both an anticipatory and preventative conception. This is grounded on an understanding of accountability where there is an active relationship between stakeholders and a forum where the conduct of those stakeholders is uncovered, debated, and justified in continuous public dialogue (Bovens *et al* 2014, Santoni de Sio and Mecacci 2021). Understanding accountability in this way permits greater synchronicity with normative political theory.

In particular, contemporary understanding of representative democracy centers on the importance of accountability as a function of citizens' capacities to self-determination, ensuring that their representatives are responsive to their values, and to ensure that those representatives can be held accountable (Palumbo and Bellamy 2010)[125]. Intrinsic to this understanding of accountability is the notion that the representatives of citizens have a real impact on public decision making processes, and that, hence, these representatives who are responsible for facilitating those processes within institutions, must be sufficiently responsive to the citizens and their values (Schuppert 2014), and not too late in the process. As a consequence, what should arise to promote public dialogue are deliberative spheres where citizens are encouraged to make their voices heard in decision making processes with at least some connection to the relevant decision-making processes and some interaction between the represented and their representatives (Fung 2006, Grunwald *et al* 2006).

Still, this does not entail that such deliberative spheres are necessarily meaningful. It has thus been argued that participatory spheres should be created where real influence on policies can actually be exerted (Paterman 1970, pp 70–71). This, of course can lead to certain asymmetries in participatory spheres where Pareto distributions lead to certain individuals or groups who garner more influence and control to have, similar as in lobbyism, a disproportionate amount of decision making control, thus influencing policy outcomes often to their own benefit (Papadopoulos and Warin 2007). This, consequently, means that this understanding of accountability may reinforce existing spheres of influence and destabilize the equal opportunity of citizens and stakeholder groups to participate in public decision making concerning science, technology and innovation. However, there has been research that suggests that equitable forms of accountability can be designed into substantive forms of representation to ensure that policy outcomes reflect individuals or groups with less structural influence or power (Page *et al* 2013, Grimes and Esaiasson 2014). These forms of accountability include structural mechanisms to uncover and scrutinize potential conditions of power imbalances where certain agents or groups may cease to reflect the values of stakeholders in decision making arenas (McGeer and Pettit 2015).

Accountability thus concerns forward-looking governance frameworks, policy choices, spheres, and continuous mechanisms to check undue power asymmetries. If we aim to understand accountability viz. Normative political theory, then it becomes *de facto* multidimensional. It involves those who do the accounting and those who are accounted for, it provides the shared guidelines for how behaviors are to be reported, justified, and assessed, and, finally, how violations are to be sanctioned and how those sanctions are to be enforced[126].

One final caveat to explore here might be the distinction between focusing on the instrumental and intrinsic value of democracy. One might presuppose that democracy as an intrinsic value should always prevail. We argue that this is not the case. Democratic approaches are not merely ideological, they have practical value for their adopters, especially in commercial and industrial

[125] Of course, there is no consensus concerning a single understanding of political accountability. For more, see e.g. Bellamy *et al* (2011) and Pitkin (1967).
[126] For greater depth on the mechanisms of this multi-dimensional understanding of accountability see Buchanan and Keohane (2006).

contexts. Stakeholder engagement at an early stage might reduce the risk of a product being rejected at launch, hence enabling companies to invest higher amounts or the industrial designers to work more freely on the product. Similarly, widening the base of participation on the development of a technology can attract diverse talent to the field and support innovation processes to explore the section of the opportunity space that was previously inaccessible. Policies developed and implemented by companies to realize these outcomes *de facto* support democratization of a technology in general. However, it might be an open question whether this is acceptable when public policies are enacted where a democratic approach is adopted due to its instrumental value. A for-profit company utilizing deliberative processes to maximize the adoption of its software stack by its potential future user base should in essence be distinguishable from public bodies' attempts of including and informing stakeholders to support the democratic process.

Table 3. A matrix of value type and democracy theory with several examples of how actions can be formulated.

	Instrumental value	Intrinsic value
Deliberative democracy	• Including stakeholders to support the technology development and/or Adoption • Informing the stakeholders to reduce hesitancy towards the technology due to uncertainty	• Including stakeholders for betterment of the deliberation process • Informing the stakeholders to empower them for them to better present and defend their positions for deliberation
Participatory democracy	• Raising awareness to justify public funding • Supporting education efforts for workforce development	• Raising awareness to inform the public and remove the enigma element • Supporting education efforts to distribute expertise among the public and empower citizens
Representative democracy	• Aiming for representation from the widest possible majority of stakeholders to support the ecosystem and market formation efforts	• Aiming for representation from the widest possible majority to have most of the public's interests represented

The layer of accepting democracy as an intrinsic or instrumental value can be thought of as an additional dimension to the distinctions between having different theories of democracy, clear identification of direct and indirect stakeholders, and formulating compatibility between different modalities of action (back end and front end). This can be briefly described as whether utilization of a democratic approach for a situation is assumed due to its instrumental value (i.e. it would yield beneficial outcomes) or accepted as an intrinsic value. Some examples on how the same actions can be formulated with different values is given in table 3.

In summary, democracy cannot and should not be viewed as monolithic but rather as multi-faceted with various approaches that can be taken to open-up democratic modes in science and technology research and development. Here we have highlighted three approaches in democracy theory and practice as well as how they are of instrumental and intrinsic value. We have likewise highlighted some modalities of applied democratization in innovation.

In the following section, we will first focus on how the notion of democratization is used in the quantum computing field, and afterwards discuss narratives and actions that support or obstruct efforts of democratization.

3.Democratization in quantum computing

The democratization of any given domain is not an obvious or straightforward means by which to include important stakeholders in how science and innovation progress. We discussed three democracy theories that may be useful for democratization in the realm of science, technology, and innovation. In the first part of this section, we look at the actual efforts geared towards the democratization of quantum computing. The second and third parts explore the various narratives around democratization of QT more broadly.

Quantum computing promises the ability to make certain calculations possible that supercomputers can practically not perform. For example, it may offer the possibility to simulate (chemical and pharmaceutical) materials much more efficiently, enabling previously not possible research and development avenues to explore, with considerable societal impact (Möller and Vuik 2017). Considering that the potential uses of quantum computing are yet to be discovered but expected to be societally relevant, some have argued for accessibility as a core value for the field (Coates *et al* 2022, p 9, Coenen *et al* 2022, p 5). In the following part, we introduce efforts by actors in the quantum computing field to realize this, and how it connects to the discussions on democratization.

3.1 Efforts in democratization of quantum computing

In May 2016, IBM put the first quantum computer in the cloud (Mandelbaum 2021) for it to be accessed by anyone interested in this technology. Following this, they announced and developed Qiskit, an open-source software development kit for working with quantum computers at the level of circuits, pulses, and algorithms (Gambetta and Cross 2018). These efforts by IBM are still ongoing (Wootton *et al* 2021).

Briefly, IBM's efforts for education and outreach of quantum computing are[127]:

- First open access quantum computer in 2016.
- Over 100 M USD investment into quantum education efforts in the last five years.
- Three million people reached via tools like the Qiskit textbook, YouTube channel, hackathons, summer schools, and so on.
- IBM Quantum Internship accepts and trains 135 students yearly.

[127] Numbers obtained from the 'Panel discussion: how do you build a quantum workforce? What is a good way to ascertain what knowledge level and number of experts is required?' This panel was organized on May 18th, 2022 at the Commercialising Quantum 2022 event by The Economist, numbers were given by Liz Durst, Director of the IBM Quantum & Qiskit Community.

These efforts are mentioned in detail here, because this approach is adopted widely for discussing the democratization of quantum computing, which puts a strong emphasis on putting quantum computers in the cloud and providing access to the widest possible range of users, and acknowledged in the literature (Ten Holter *et al* 2022). Similar efforts and approaches to IBM in this field are adopted by others in the community. Quantum computing hardware developers such as D-Wave and Xanadu are also quite actively supporting the open cloud access model. D-Wave has an applications database with more than 250 early quantum applications available[128]. Xanadu has a programmable photonic processor in the cloud that achieved quantum computational advantage (Madsen *et al* 2022). Providing access through the cloud and supporting this access with complementary (such as educational or case-study based industry-oriented) activities can be understood as the main arc of the democratization as it is conceived of in the quantum computing field.

Here nuanced distinctions can be made between the uses of the terms 'democratization' and 'democratizing access,' and between the intended target groups. Although sometimes they are used interchangeably (Grossi 2021), these two terms signify different concepts, as democratizing access can be a part of the democratization efforts, but democratization is a concept that (potentially) encompasses a wider set of actions, including but not limited to *engagement with indirect stakeholders*.

Similarly, some in the field advocate that democratization is for anyone with an internet connection (IonQ 2022), while others posit it as primarily for developers and researchers (Osaba *et al* 2022, p 55808), and sometimes particularly for non-quantum experts (Liscouski 2021).

Arguments for the necessity of democratization in quantum computing from a pragmatic point of view usually rely on the phenomenon of workforce or talent shortage (NSTC 2021, 2022). There are already studies on describing the landscape of the quantum workforce (Kaur and Venegas-Gomez 2022) or assessing the talent needs of the quantum industry (Hughes *et al* 2021). In this regard, a discussion among the community on who needs to be educated in QT, on which topics, to what extent, and for which purpose can also be thought of in its correspondence to the democratization of quantum computing, as introduced above. It is closely related to the distinctions between direct and indirect stakeholders (see section 2), and whether democratization requires access by only direct or both types of stakeholders, and to the question of whether democratizing access to quantum hardware necessarily entails a reduction of the entry barrier to obtain the required skills to utilize that access or not.

The topic of access to quantum hardware is an analogue of the comparison provided in table 2 between front end and back end for education. Realization of quantum computers that are commercially active contains the risk of deepening the existing societal divides and inequalities (de Wolf 2017, Ten Holter *et al* 2021). A back end motive would be to have distributed expertise and a widespread understanding to distribute the benefits generated by these devices to the widest possible reach, however, this does not directly translate to front end since different identifications of direct stakeholder ship would yield distinctly different actions to be adopted.

[128] www.dwavesys.com/learn/featured-applications/

Similarly, the trend of leading companies rushing to put their devices freely available on the cloud in an attempt to democratize access can be better understood through them taking democracy as an instrumental value. As listed on table 3, creating a user base helps with reducing hesitancy towards the technology, supports education efforts for workforce development, and aims at increased adoption of the technology to support the ecosystem and market formation efforts. In this regard, companies that manage to reach out to most early users might get strong first mover advantages as the ecosystem and market formation are path-dependent processes. On the other hand, there are many public and grassroots initiatives that are enabled by the actions of these companies. These initiatives aim at raising awareness, inclusion of the widest possible majority, empowering stakeholders, distributing expertise among the public, and much more. Their aims align with taking democracy as an intrinsic value, supporting democracy for the sake of democracy. In the case of companies, their motives are understandably aligned with commercial interests, nonetheless enabling adoption of actions by other actors to further democratize the field.

In the literature, access is not always necessarily associated with the term democratization, and we can clearly see this from the previous literature that advocates for making this technology accessible in one way or another (de Wolf 2017, Johnson 2019, Coates *et al* 2022, Coenen *et al* 2022). As an example, in the Insight Report on Quantum Computing Governance Principles of the World Economic Forum, the stakeholders are listed as governments, academics and universities, international organizations, corporations, private entities that are developing and using the technology, developers, and consumers (Coates *et al* 2022, pp 7–8). In this report, the public is located as an entity that needs to be educated (p 5) and enlightened (p 7), and the deliberations are to be held among stakeholders (p 8; p 19). The report makes no references to democracy or democratization, but in the taxonomy provided above, one might argue that it is implicitly advocating a model similar to the *deliberative theory of democracy* that limits deliberation to direct stakeholders.

A different argument in the literature without explicitly invoking the terms democracy or democratization is found via the term ‘public good’ (Roberson *et al* 2021). In this literature, authors argue for QT to benefit the societies they will be used in, and maintain that the notion of ‘public good’ should be extended beyond its traditional conceptualization by economists who describe public goods as those which can be used by many without reducing the availability of said goods. They argue for it to be determined through processes of reasoning and engagement between science and society (p3). This requires wider public consultation and engagement if QT should work for a broader societal good. They highlight that current national strategies are formulated in a narrow sense of public good based on themes of increasing national competitiveness and concerns over threats to national security (p5), which can be considered as a premature ‘imaginary lock-in’ (Mikami 2015) to certain visions by a group of experts focused on realizing a narrow set of futures at the expense of alternative potentialities. This argument can be extended to the limits of social shaping of QT, where a lack of public clarity regarding concrete expectations for QT prevents specific engagement around societal impact (Roberson 2021a, p394). Premature lock-in to certain visions via national narratives limit wider public consultation and engagement, hence limiting the impact of social forces on shaping the trajectory of QT. Finally, it is discussed that for a responsible development of QT, increasing

public awareness is the absolute minimum that needs to happen (Coenen and Grunwald 2017, Roberson 2021b). These points in the literature signal that there needs to be further discussion on public engagement and democratization of QT, even if in the end society just endorses the prematurely locked-in visions by national strategies. This approach is more in alignment with *participatory democracy* in the taxonomy given in section 2, where the whole of society (whether they are direct or indirect stakeholders) should be included in the process of guiding the development trajectory of QT.

A third overall tendency that can be observed in the quantum community and previously mentioned in the literature is through community membership, advocacy, and 'the maker movement' (de Wolf, 2017, p275), which can be associated with the *representative theory of democracy*, but one that is enriched by deliberative and participatory approaches. This is mainly enabled by public investment programs (like the Quantum Community Network (QCN) under the EU Quantum Flagship[129] and the Quantum Future Academy[130]), companies that are developing quantum hardware and software resources (spearheaded by IBM with the Qiskit Advocate initiative[131]), by the formation of online global grassroots communities[132] (such as QWorld, OneQuantum, Full-Stack Quantum Computation, and so on) that lowers the entry barriers to the field of quantum computing, and by communities focusing on special interest groups[133] (such as Q-munity for high school students, Girls in Quantum for girls and students, Women in Quantum Development (WIQD) for female professionals in QT, Q-Turn (Sainz 2022) for researchers from marginalized groups, and so on). These efforts do not mainly discriminate between direct or indirect stakeholders and promote the widest possible representation in the QT space. QCN has leading researchers representing their countries, Quantum Future Academy hosts two students from each countries selected by national scientific institutions, Qiskit Advocates act as mentors and liaisons between enthusiasts and IBM's resources, grassroot communities such as QWorld and OneQuantum have local branches in more than 25 countries with *de facto* national representatives of the local quantum grassroots communities, and communities such as WIQD and Q-Turn aim to give voice to researchers representing certain interest groups. All these efforts can be viewed in alignment with a *representative theory of democracy after the deliberative and participatory turns*, where different stakeholders and populations contribute and become a part of how *the second quantum revolution* unfolds via certain representatives acting as intermediaries.

As listed above, approaches in line with one or more of the three theories of democracies can be seen in both the literature and the practice of quantum computing, with a particular focus on awareness raising and education due to the phenomenon of workforce or talent shortage. In the next subsection, we will focus on narratives and actions against democratization in quantum computing and QT more generally.

[129] https://qt.eu/about-quantum-flagship/the-quantum-flagship-community/quantum-community-network/
[130] http://www.quantentechnologien.de/bildung/quantum-futur-akademie.html
[131] https://qiskit.org/advocates/
[132] https://qworld.net/, https://onequantum.org/, https://fullstackquantumcomputation.tech/
[133] www.qmunity.tech/, https://girlsinquantum.com/, www.wiqd.nl/, www.q-turn.org/

3.2 Narratives and actions against democratization

In the current QT ecosystem, we observe three major obstacles for opening up QT to a wider public engagement process that also incorporates a diverse set of perspectives from different groups of stakeholders. These are the narratives of, (a) QT as an arena for geopolitics, (b) quantum mechanics as incomprehensible, and (c) quantum computing as a threat to the cyber-infrastructure. In this subsection, we first describe and analyze these narratives and related actions. As a next step, we will discuss the counter-narratives and actions against these obstacles.

3.2.1 QT as an arena for geopolitics

The first narrative is the one of QT as an arena for geopolitics, and its discussion takes up the larger part of this subsection. It is widely accepted that there is a *quantum arms race* going on (Giles 2019), mainly between the US and China, but encompassing a wide range of alliances. Reflections of this line of thinking can be seen especially regarding international collaboration. Quantum computing and QT in general have been a topic of geopolitics for some time.

Export controls under 'The Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies' are implemented for some of the QT (Bureau of Industry and Security 2019), and the US International Traffic in Arms Regulations (ITAR) and the Export Administration Regulations (EAR) are proposed to make hiring foreign talent challenging (GAO 2021, p 41). Also, there are special arrangements and limitations on cooperation between certain countries (Ten Holter *et al* 2022), and it has been discussed previously that the global cooperation between rivaling powers was fizzling out (Biamonte *et al* 2019) even before the SARS-CoV-2 pandemic and the invasion of Ukraine. Certain application areas within QT are in direct alignment with military and defense industries, such as positioning, navigation and timing, cryptography, and high performance computing. Furthermore, historically (especially in the United States), new technologies have been funded by military efforts first and civilian applications followed later.

Finally, a kind of vigilant technology sovereignty argument is accepted as a legitimate point to argue for public funds in an increasingly tensioned global political stage that brings together the technological superiority narrative with the 'Might makes right' mindset. For a recent example, the newly formed AUKUS, a trilateral security pact between Australia, the United Kingdom, and the United States, has QT under its advanced capabilities areas for cooperation and an arrangement titled 'The AUKUS Quantum Arrangement (AQuA)' is set up to accelerate investments to deliver generation-after-next quantum capabilities (The White House 2022). These technologies are sometimes presented as 'transformational technologies' or 'game-changing advances' (McKay 2022, p 6) for the military branches such as the US Air Force.

This is mirrored by efforts in China, where, following the Snowden Revelations, a considerable effort to 'hack-proof' their critical infrastructure was initiated (Chen 2014). However, it has been shown that research on quantum cryptography in China preceded 2013, and China has been a leading actor in scientific efforts on quantum cryptography, at least quantitatively, since 2007 (Olijnyk 2018). This can also be observed in terms of patents, as China has become the country

with most patents granted in QT (Seskir and Willoughby 2022b) in a decade via an aggressive patenting policy.

A similar stance can also be observed in the European Union, as phrases like 'Ensuring security and technological sovereignty' (Castelein *et al* 2020, p 37) or '..reaching its political ambition in QT, in order to safeguard European strategic assets, interests, and security…' (Quantum Flagship 2022) can apparently be encountered more often than before. So, overall, QT is presented as an arena for geopolitics by some actors of that arena and of the QT community.

These points enable national actors to prioritize certain militarized visions of QT against others, even before they are brought forth to the public arena for discussion, and this poses a major obstacle in democratization of QT in four different respects. First, it is creating a reasonable ground for diversion of research funds to organizations with security priorities rather than scientific ones. One concrete example of this is the work on quantum radar (Lanzagorta 2011), which relies on a technique called quantum illumination (Lloyd 2008), where most of the research is conducted in organizations either directly working with militaries or in close association with them (Durak *et al* 2022). News articles starting with sentences such as 'A new quantum radar technology developed by Chinese scientists could detect stealth aircraft…' (Chen 2021) are part of a discourse that reinforces the militarized priorities and strengthens the mode of thinking that supports restricting access to knowledge, instead of increasing it.

The second point is the exclusion of students and researchers from certain backgrounds. In recent years, there were discussions over the FBI visiting American universities '..with an unclassified list of Chinese research institutions and companies' (Feng 2018), asking them to monitor students and researchers from these institutions and companies. Although calls for keeping quantum computing research open were being made (Biamonte *et al* 2019), now the field is becoming more and more separated between geopolitical blocks. This has direct consequences for democratization efforts. For example, certain grassroots communities that operate in the EU and the US ceased their operations in Russia and China in the last few years and some do not even accept participants to their otherwise globally open events from these regions. Companies, especially start-ups, sometimes refrain from collaborating with partners that also have or had collaborations in these countries. Furthermore, it is sometimes openly discussed that access to not just devices, but also the knowledge networks should be restricted, not only to researchers in Russia or China, but to any researcher that is operating outside of the states governed by 'like-minded governments'.

The third point is the exclusion of researchers that for one reason or another prefer not to work in alignment with military objectives on certain research topics. There are statements in the literature on 'Should QST support war?' (McKay 2022) or even 'Should We Build Quantum Computers at All?' (Chen 2022). There are active members of certain quantum communities referring back to their unknowing involvement in defense-related projects in QT during their graduate studies and how it actually drove them to dropping out of academia. There are some departmental customs in many academic institutions (especially in social sciences) that discourage researchers from getting involved in defense-related topics. As QT becomes more

militarized, it may repel researchers with a focus on social justice and then evade scrutiny by those that may otherwise propose interventions on the trajectory QT is progressing in.

The final point regarding the first narrative is the reduction in awareness-raising and outreach activities as certain parts of QT become militarized. As militarization of a technology excludes certain researchers from entering the research domain, it also limits the amount of information that is getting out of the research labs. Researchers involved in defense-related projects may do less outreach, collaborate more internally, and rarely engage in citizen science activities—regardless of the question if the researched technology will ever be field-deployable.
A counterargument to the points we presented above can also be developed. It can be said that militarization of QT in the democratic countries is a necessary act to preserve democratic values by empowering the forces that protect these countries, and by extension the values. This, although hampering the global democratization process, from a larger perspective is enabling the preservation of democratic values. This argument, however truthful it may be from a conflict-oriented geopolitical understanding of the current global politics, still does not negate the fact that militarization of QT results in: (a) prioritization of military visions/needs against other societal stakeholders (even in a local scale), (b) introduces certain types of exclusionary mechanisms for stakeholders with particular backgrounds (either foreign students or researchers that are skeptical of the militarization process), (c) reduces transparency on how these technologies are being developed and adds a time pressure on them to make them field-deployable as soon as possible.

Now, let us examine how these translate to obstacles in accordance with the three democracy theories we introduced in section 2. First, the militarization of a domain grossly reduces the number of relevant direct stakeholders in a technology field, hence, it skews the representational landscape to prioritize the representation of certain (military and security-oriented) stakeholders against others. Second, it actively aims at creating friction in the flow of information, reducing transparency, and raising the entry barrier for potential stakeholders that are outside of the militarized domain, making it harder to participate in the development of these technologies. Finally, the time pressure and reduction of awareness-raising and outreach efforts directly contradict the deliberative process, which limits the deliberation process both in terms of the range of options (due to reduced levels of awareness in stakeholders) and in terms of time horizon. In these regards, it is clear to us that defining the current state of QT as an *arms race* and as an arena for geopolitics calls for the militarization of the field, which is an obstacle for opening QT to a wider public engagement process that also incorporates a diverse set of perspectives from different groups of stakeholders under any of the definitions of democracy, we introduced in section 2.

3.2.2 Quantum mechanics as incomprehensible

The second narrative is about quantum mechanics being incomprehensible. Richard Feynman famously wrote, ‘I think I can safely say that nobody understands quantum mechanics’ (1995, p 129). Feynman was however equally famous for making physics, including quantum mechanics, understandable, yet this quote has acquired a life of its own to emphasize the opposite. One iteration of the quote is used in a 2013 article by the science writer Philip Ball at BBC titled ‘Will we ever… understand quantum theory?’, citing a survey study on foundational attitudes toward

quantum mechanics (Schlosshauer *et al* 2013). Ball reassures his audience that if 'the baffling behavior of subatomic particles leaves you scratching your head with confusion, do not worry. Physicists do not really comprehend it either.'

This is just a single example out of a myriad of popular science articles, news pieces, and presentations for the purpose of education or outreach on quantum mechanics; so much so that it is a common practice among physicists giving public talks to quote Feynman, saying that quantum mechanics is not understandable, and then try to make their audience understand quantum mechanics. This issue gets further complicated as promoters of pseudoscientific ideas such as quantum healing (Chopra 1990), quantum mind, and quantum consciousness utilize this approach. The quote and the argument behind 'nobody understands quantum mechanics' plays into their narrative: where nobody understands something, the line between science and pseudoscience gets blurred.

Examining this narrative with the lens of the three democracy theories, it is relatively straightforward to observe that it limits legitimate participation into the development process of QT to a small group of experts that somehow manage to make the technology work, even though they also do not fully understand it. It thus effectively blocks democratization efforts in the sense of the participatory and representative theories, and does so even for the future by declaring that citizens cannot ever be in the position to meaningfully decide about QT. It thus practically makes public deliberation about QT impossible under all three democracy theories, leaving us again with limited deliberative democratic control by small expert groups.

3.2.3 Quantum computing as a threat

The final narrative is quantum computing as a threat. In 2014, following the Snowden Revelations of 2013, an article came out in the Washington Post titled 'NSA seeks to build quantum computers that could crack most types of encryption' (Rich and Gellman 2014). This article gives an overview of the efforts by The National Security Agency of the United States Department of Defense, that covers ominously named projects such as 'Penetrating Hard Targets' and 'Owning the Net.' In 2015, the Information Assurance Directorate (IAD) under the NSA and the Central Security Service declared that no commercial security algorithm suite is considered secure in the long run anymore by the IAD. In a document titled 'Commercial National Security Algorithm Suite and Quantum Computing FAQ,' (2016) they stated that auxiliary measures should be taken '..while waiting for quantum resistant algorithms and protocol usage to be standardized' (p 5). This is due to Shor's algorithm (1997), which is one of the few quantum algorithms that can prove an exponential speed up for a mathematical problem against its best-known classical counterparts. The mathematical problem in question for Shor's algorithm is prime factorization. It is part of several essential cryptographic algorithms that are widely used for asymmetric public-key cryptography, which secures online transactions between different parties for many purposes such as messaging, sending images, sharing sensitive data (like credit card information for online shopping), and so on. This revelation fueled a narrative that was already there: quantum computing is a threat to the entire cybersecurity infrastructure of the internet as we know it.

A report published by the Global Risk Institute (Mosca and Piani 2022) containing the results of a survey conducted with over 46 experts in the field shows that the majority of respondents estimate that a quantum computer able to break RSA-2048 in 24 h is not going to be around in ten years, and they deem it only partially likely in 15 years. According to the survey the real threat horizon begins only after 20 years.

Furthermore, these estimates are for RSA-2048, which is highly unlikely to be still used in 20 years. Still, it can be rightfully argued that breaking these algorithms can cause serious problems to data privacy and particularly pose a danger against sensitive data that requires storage for a long time (20 + years). Hence, the final obstacle, portrayal of quantum computing as a threat is a narrative frequently encountered.

This narrative both feeds into the first narrative of QT being an arena for geopolitics and it frames the technology as dangerous, causing protectionist impulses (Ten Holter *et al* 2022) by certain actors to limit the distribution of even much smaller quantum computers that in no way pose a threat by such means as the Wassenaar Arrangement. This framing of quantum computers as potential weapons that can lay waste to the infrastructure of the internet, which is almost an essential utility for the modern society to function, triggers questions such as 'Should We Build Quantum Computers at All?' (Chen 2022). The answer given to this is usually along the lines of 'X is already building it, they will build it even if we do not,' where this X changes depending on who you ask. This narrative acts as a means to frame the technology in a certain manner that justifies limiting participatory and deliberative processes, nudging the representation space to a more securitized configuration where direct ownership is allowed only to a selected few. Posing quantum computers as a threat is the epitome of creating a justification for restricting access, especially as the technology matures. Similar to the QT as an arena for a geopolitics narrative, the quantum computing as a threat narrative also supports the introduction of exclusionary mechanisms to the participatory efforts. It creates time pressure on the potential deliberation process and prioritizes certain (security-oriented) stakeholders' needs over others.

Until now in this section, we presented three of the narratives that act as inhibitors for an inclusive public engagement process, which are (a) QT as an arena for geopolitics, (b) quantum mechanics as incomprehensible, and (c) quantum computing as a threat. There are other obstacles and narratives that can also be formulated as potentially inhibiting the democratization process. We chose these three since they were already pointed out in one form or another in recent literature (Coenen *et al* 2022, McKay 2022, Ten Holter *et al* 2022), and often are a topic of informal conversations or conference talks within the QT community. In the following part, we present some alternative points and actions that can be adopted instead of these narratives.

3.3 Counter-narratives and actions supporting democratization

There are narratives and actions in the QT community that counter the three narratives described in the previous subsection. First, regarding the narrative representing QT as an arena for geopolitics, a militarized technology is almost by definition not a democratized one. Under any of the three democracy theories, excluding the majority of the public and enabling a selected group access to the operational capabilities of a certain set of technologies, cannot be

argued for without some serious supporting situational conditions. Having said that, a democratic technology can still be utilized for military and defense purposes; even though it might be less effective in 'keeping the fight unfair' (McKay 2022). Furthermore, discussions on how to balance the risks and responsibilities of stakeholders in this domain can be found in the literature (Roberson 2021b).

For an inclusive process, it should be acknowledged that the world consists not only of hegemonic powers, and QT has the potential for much more than just being another arena for technological competition between them. Civilian uses of QT should be emphasized and how they can be utilized in a way that benefits the common good (Coates *et al* 2022, p 9), such as via the Sustainable Development Goals (Coates *et al* 2022, p 16). Civilian uses should be given primacy over creating benefits to operational capabilities of certain military branches. Furthermore, the most coherent response to the misuses of these technologies can be better formulated with international agreements and other forms of stakeholder action (Silbert 2022), rather than with siloed approaches in different global camps. Finally, there are already calls in the literature that 'a responsible innovation mindset requires us to think in potentially more creative ways about national approaches, ownership of such technologies and protectionist or nationalistic approaches' (Ten Holter *et al* 2022).

Second, regarding the narrative on quantum mechanics being incomprehensible, counter-narratives and actions exist too. As noted earlier in this section, IBM alone spent more than 100 M USD on quantum education efforts in the last five years. There is a committed section of the Quantum Flagship focused on QT education[134], research institutes reach out to the public at large to make QT understandable[135], and there are many companies and communities focused on education efforts in QT. There are many innovative approaches such as utilizing games and interactive tools/textbooks (Wootton *et al* 2021, Seskir *et al* 2022b), considering quantum mechanics as a generalized probability theory (Aaronson 2013) and organizing community-based workshops (Salehi *et al* 2022). All these efforts rely on the assumption that one does not need to be a seasoned physicist to understand quantum mechanics on a level to be operationalized for the purposes of utilizing QT.

The foundations of quantum mechanics are full of surprising and sometimes confounding ideas and discoveries. This does not mean, however, that quantum mechanics is incomprehensible, and it surely does not support the Feynmanian position that 'nobody understands quantum mechanics.' For a technology to operate and be adopted by the public, it needs to be understandable, it needs to be 'normal' in a Kuhnian sense. Although one might find Feynman's quote interesting or even funny and aims to use it to instill some sense of wonder and mystery, it is working against the basic assumption that motivates all the outreach and education efforts. It raises the entry barrier to newcomers, it might encourage some that are particularly tuned to challenging this quote, but this will only be a small minority of the public. For an inclusive public engagement process, this narrative should go, and a new one that portrays QT as more normal

[134] Quantum Technology Education: https://qtedu.eu/.
[135] TU Delft has vision teams projects that create dialogues with society about perspectives on quantum technologies (Vermaas *et al* 2019) and www.tudelft.nl/en/about-tu-delft/strategy/vision-teams. And other institutions (such as KIT) are creating dedicated offices to make QT more understandable and knowledge on the topic more accessible by the public.

and mundane be developed: one that is open to participation from all parts of society, one that can be understood through getting involved, and one that is based on science, not mysticism. Interpretations of quantum mechanics can play a role in making QT comprehensible (Vermaas 2017) as they are descriptions of what the world would be like if quantum mechanics is true. In fact, one could even argue that the descriptions of atoms and qubits that are to be used by engineers working in QT for making these technologies more comprehensible can help favor a specific engineering interpretation of quantum mechanics (Vermaas 2005).

Table 4. Narratives as obstacles for inclusive public engagement and some alternatives.

Narratives	Alternatives
QT as an arena for geopolitics	• Accept that the world consists of more than just hegemonic powers, avoid protectionisms • Focus on civilian uses related to sustainable development goals
Quantum mechanics as incomprehensible	• Feynman's quote should only be used within its proper context, and not to implicate that people cannot understand quantum mechanics • QT needs to become a 'normal' (and even mundane) technology, pseudoscience should be criticized
Quantum computing as a threat	• Focus on ways to constructively deal with threats (such as the NIST process) • Present realistic timelines, not only the worst-case scenarios

Finally, regarding quantum computing as a threat narrative, in 2016 NIST announced that it will be collecting nominations for public-key post-quantum cryptographic algorithms. For over the last five years, a period of open testing has been going for over more than 80 algorithms that were initially submitted.

Currently, in Round 3, there are seven main and eight alternate candidates. Even though the process is not finalized yet, some cyber infrastructures already started adopting post-quantum algorithms (such as OpenSSH 9.0 adopting NTRU Prime algorithm[136]). This does not mean that the post-quantum algorithms are entirely secure, it is an active research area and recent research reveals some vulnerabilities in some algorithms that are considered as finalists by the NIST (Karabulut and Aysu 2021), requiring the algorithms to be updated. Similarly, the European Telecommunications Standards Institute (ETSI) is working on migration strategies and recommendations for quantum-safe schemes (ETSI 2020). All in all, it can be safely said that the issue of 'quantum computing as a threat' is being taken seriously, and several institutions around the globe are working on providing solutions, guidelines, and strategies to prevent negative scenarios.

[136] Patch notes for the release: www.openssh.com/txt/release-9.0.

To sum up: We have identified three narratives as major obstacles inhibiting an inclusive democratization process on QT and provided some possible ways to remove these obstacles and alternative narratives to replace the current ones (see table 4). Education efforts to make quantum mechanics and QT understandable to all may be taken as democratization under all three theories of democracy; the other mentioned counter-narratives and efforts may be directed to and enable only a limited group of stakeholders, fitting more deliberative democracy. The reasons these narratives are widely adopted in the community are more complex than the explanations that we provided. Of course, the alternative narratives we offered are not the only possible ones, and we do not argue that they are necessarily the best alternatives either, but they can act as starting points for more constructive discussions.

In the following section, we expand the discussion to explore the nuances of democratization regarding different QT, how public participation already is and further can be included in this process of democratization.

4. Toward more democratization in QT

Many of the efforts and narratives we discussed so far may support democratization of QT. In this part, we highlight two main lines of discussion: the topics of access and participation. Finally, we ask what else can be done and how shifting focus to more overarching points might provide further insights.

4.1 Enabling access

In section 3 we pointed out that enabling access to quantum computing hardware is associated with democratization. Several authors have argued that such open access is essential for quantum computing (de Wolf 2017, Kop 2021, Ten Holter *et al* 2021, Coates *et al* 2022, Coenen *et al* 2022). For the particular case of quantum computers this makes sense—however, QT is more than quantum computing.

For quantum computing one could argue that giving general access is practically and economically feasible since it can be organized by existing cloud infrastructure. For the other QT providing access may prove to be much more difficult. Consider, for instance, democratizing access to quantum key distribution (QKD) devices. Current costs of QKD devices are around 100 k€ for reasonable systems that can handle modest key rates (KEEQuant 2021, p 8). Even assuming a hundred-fold reduction in cost, providing access to QKD for all the households in the EU would cost approximately 200B€. One might argue that democratization in this case means giving access to QKD devices by avoiding legislation that would limit public use of QKD. But arguing for widespread distribution of this technology for democratization leads nowhere due to the simple reason that the required funds do not exist and will not exist for the foreseeable future.

A different discussion can be made for quantum sensors. Access to classical sensors (such as gyroscopes, cameras, ranging devices) are common, each smartphone contains a considerable number of sensing tools. This does not mean that users are well-educated on how sensors work, most are even unaware that they have these devices in their smartphones. It was noted in a public dialogue report published by the Engineering and Physical Sciences Research Council

of the UK (2018) that participants were '..confused, disengaged or neutral and communicated finding the topic difficult to understand' (p 8) when the inner workings of gravity sensors were presented to them, but they responded more positively after learning that such devices can be used for climate monitoring (p 26). This again brings forward the question of what exactly should be democratized when such complex and layered technologies are in question: access to the underlying mechanics or the products utilizing those low-level physical properties for operations that are more recognizable by societal actors and stakeholders. Deliberative processes with stakeholders and citizens more broadly on applications of QT thus may be particularly effective democratization measures.

Another interesting aspect is the democratization of research tools and results within the QT community. To quote one example concerning research on qubits, the basic key components in quantum computers:

> There are other ways to democratize spin qubits. One can distribute known good devices to academic groups interested in exploring new qubit encodings and ways to control them; this is the foundry model. Increasing throughput of testing at multiple temperature stages (room temperature, 1 to 4 K depending on the physics, and <100 mK) also directly benefits fabricated device optimization. (Tahan 2021, p 3)

Although it is not framed in this manner in the given example, this is a particularly valid and valuable discussion as the high costs of devices limit the participation of researchers from the Global South. Increasing the number of facilities globally has practical benefits for research and development purposes as well. It enables access to local talent, it gives access to some national funding as included countries are most likely to divert funds into the topic, and it promotes the research topic in further regions. Regardless of accepting democracy as an instrumental or intrinsic value, distribution of research among international academic groups, and bringing developing nations onboard has some merit that needs to be taken seriously.

To sum up, whether access is necessary or sufficient for democratization of QT does not have a straightforward answer. If we accept the *participatory* depiction of democracy, by not having access, a huge portion of society loses even the chance of self-selected participation. On the other hand, in a *representative* understanding of democracy, the sections that do not have direct access to these technologies can influence the development trajectory of them via representative means, for example, by supporting particular funding schemes. Furthermore, public participation and dialogue exercises, such as the one that was run by EPSRC (2018), are a great example of how a *deliberative* approach can be taken even when the public does not have direct access to these technologies. This approach may be particularly relevant when it comes to an inclusive democratic approach concerning potential applications of QT.

4.2 Enabling participation

Opportunities for public participation in the second quantum revolution is another important avenue for discussion on democratization of QT. The obvious avenue of participation for citizens is as consumers, but even that is not very straightforward, as hinted at when discussing public access to QKD. The near-term QT market is expected to be mainly B2B (business-to-business),

meaning that the public will not even be participating as consumers. This means that by the time these technologies are in the market for the individual consumers, there might be little room for them to have any say on the development trajectory due to all the path-dependencies infused into their design.

There are some options explored in the QT community to circumvent this outcome. The first one is forming lobbying groups that represent the public's interests (EPSRC 2018, p 43). The second is through participation in research activities via citizen science initiatives. Some examples of this can already be found in the literature (Lieberoth *et al* 2014, Heck *et al* 2018, Jensen *et al* 2021). The third is participating and forming grassroots communities (such as QWorld, OneQuantum, Full-Stack Quantum Computation,

Q-munity, and so on), and more specialized communities representing specific groups such as women[137] (WIQD, Women in Quantum, Womanium Quantum, etc.), researchers that are under-appreciated due to belonging disadvantaged communities[138] (Q-Turn), students from certain regions[139] (such as PushQuantum from Munich), quantum software engineers working on open source software[140] (Quantum Open Source Foundation, Unitary Fund, etc.), researchers working on combining quantum and climate sciences[141] (Q4Climate), and many others. Fourth is the companies forming such communities for outreach and education efforts (like the Qiskit Advocate program). Finally, there is a developing culture of publishing 'manifestos' in the European QT community.

One of the first and arguably the most influential manifesto in the community was published in 2016 (de Touzalin *et al*). Both the manifesto and the list of 3680 endorsers are publicly accessible[142]:

> On invitation of Mr. Günther Oettinger, Commissioner for Digital Economy and Society and Mr. Henk Kamp, Minister of Economic Affairs in The Netherlands, a European team has been working on a "Quantum Manifesto" to formulate a common strategy for Europe to stay at the front of the second Quantum Revolution. The Manifesto will be officially released on 17–18 May 2016 at the Quantum Europe Conference that The Netherlands is organizing in Amsterdam in cooperation with the European Commission and the QuTech center in Delft.

This was followed by several other manifestos open for endorsement such as the Quantum Software Manifesto (Ambainis *et al* 2018), The Talavera Manifesto for Quantum Software Engineering and Programming (Piattini *et al* 2020), and the Quantum Energy Initiative (Auffèves 2022) with varying numbers of signatories, usually around a few hundreds, and by a manifesto that did not look for endorsement and focused on ethical and societal issues (Coenen *et al* 2022).

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[137] www.wiqd.nl/, https://onequantum.org/women-in-quantum/, www.womanium.org/Quantum/Computing.
[138] www.q-turn.org/.
[139] www.pushquantum.tech/.
[140] https://qosf.org/, https://unitary.fund/.
[141] https://q4climate.github.io/.
[142] http://qurope.eu/manifesto.

The different modes of participation also differ in their correspondence in how they relate to democratic representation. Grassroot communities and lobbying groups enable enthusiasts and the members as stakeholders to either elect *de facto* representatives of their interests within the given domain of public debate or create participatory spaces where the democratic process takes place on a smaller scale. The route of publishing manifestos calls for deliberation on several aspects. For example, the formation of the Quantum Energy Initiative (Auffèves 2022) raises questions on whether energy efficiency should be endorsed as a core design value for developing QT, and if so, what does this entail? Furthermore, there are proposals for sets of 'core values' of QT such as accountability, inclusiveness, equitability, non-maleficence, accessibility, and transparency (Coates *et al* 2022, p 9) or comprehensible, specific, open, accessible, responsible, culturally embedded, and meaningful QT (Coenen *et al* 2022, p 5) that are vocalized via these manifestos and similar publications. In summary, it is a practice emerged in (mainly) the European QT community that is directly in alignment with the process of democratization as it opens QT to democratic deliberation and propose core values that also underpin democracy.

4.3 What else can be done?

As a first step towards furthering democratic participation, there must be an initial recognition that the public consists not merely of uneducated and unenlightened people but is a collection of different stakeholder groups with (sometimes) divergent interests (Stilgoe *et al* 2006). This makes public participation and engagement complicated but it is still necessary. Providing access to information, education, and actual hardware in some particular cases are good practices, but public participation in the democratic sense requires adoption of a 'strong' RRI approach which entails linking parliamentary or other core policy processes (Coenen and Grunwald 2017, p 277) to stakeholder dialogues, decision-supporting public engagement and a wide variety of other public communication activities. While this follows a deliberative democracy approach, it is beneficial regardless of the theory of democracy one adopts, given that democracy is taken as an intrinsic value and not utilized for instrumental purposes. Furthermore, other practical steps can also be taken such as supporting the co-creation, with stakeholder groups, of use cases that benefit societal goals, democratization of not only the technologies but visions as well through co-development of cultural artefacts (such as games, artworks, tv shows), opening up controversial topics to discussion—for example, the militarization of QT (McKay 2022) or the 'supremacy' debacle (Preskill 2019)—and so on.

It should be noted that democratization of QT does not necessarily enable the same tools and approaches that work for quantum computing. QT contains a wide range of technologies that are put under the umbrella of QT due to which physical phenomena they utilize. In this sense, we argue that distancing the topic of democratization from particular technological capabilities (such as cloud access) to more overarching points of discussion (such as stakeholder engagement) would benefit the community and societies further.

5. Discussion and conclusion

As QT emerges, it becomes societally more relevant. Similar to the discussions on democratizing nanotechnology (Toumey 2011), democratizing QT is not a straightforward topic. In this article, we provided some examples of how the concept is used in the community, especially for quantum computing. We argued that the term democratization should be located

in the context of theories of democracy, also with a view to the questions whether democracy is accepted as an instrumental or intrinsic value and how direct and indirect stakeholders are identified. Furthermore, we analyzed certain narratives and actions on QT that are obstacles to democratization efforts, together with counter-narratives and actions in support of democratization efforts. Finally, we introduced several practices in the QT community that are working toward more democratization in QT.

We argued that there is practical value in making such conceptual frameworks explicit. First, having a clearer understanding of the context in which the term 'democratization' is located and used allows both, developers and practitioners of policy actions (public institutions, companies, NGOs, etc) a ground on which they can formulate their aims, goals, and visions. Second, this can help translation of best practices between different technologies, programs, countries, and so on. Some of these contexts are incompatible, such as using a participatory democratic model with interest in its instrumental value versus deliberative democratic model that prioritizes the intrinsic value of democracy itself. Having a clearer understanding of which policy or program adopts what kind of an approach reduces the chance of confusion and helps not only to develop novel policies but also with respect to their implementation and assessment. It should be accepted that different actors have different roles and priorities. It is more likely for commercial actors to use democratization for its instrumental value[143], while public actors aim for policies that promote democratization itself. A model that allows one to dissect the policies into their conceptual cores and to identify the choices taken by the actors in each step can enable a richer analysis rather than just focusing on some bland indicators.

Similarly, analyzing narratives, counter-narratives, and actions by actors in the QT community in their relation to democratization efforts can also benefit from elucidation. For example, the use of certain narratives such as 'quantum computing as a threat' or 'quantum mechanics being incomprehensible' are generally not the message that most outreach efforts aim for[144]. Hence, we hope that as they are made explicit, it will become a standard to replace these narratives with more constructive ones that focus on solutions and realistic timelines against the quantum threat, and on normalization of quantum mechanics and QT to be more inclusive, not incomprehensible and only understandable by a small group of highly trained experts.

Finally, we argue that although there are some commendable initiatives within the QT community, it is not possible to call QT a democratized field. Access to either the technology or the products of it is a necessary but not sufficient condition, hence access does not guarantee agency. Efforts in identification and engagement with not only direct but also indirect stakeholders are rare (Vermaas 2017, EPSRC 2018).

Furthermore, there are narratives that act as inhibitors for an inclusive public engagement process, which act as exclusionary mechanisms. Considering that we are still in the early days of QT, having a more democratized field compared to previous emerging technologies is

[143] An example from Microsoft: '…bringing those innovators to the table and democratizing quantum so we can get solutions out quickly' (Commissariat 2022).
[144] The proposal to not use the Feynman quote and argument of quantum mechanics being incomprehensible received particularly positively by practitioners of outreach in QT whenever we presented this paper during preparation process.

possible, but it requires reflexivity and responsiveness by the community, which may provide us ‘a chance to repair classic(al) mistakes’ (Ten Holter *et al* 2022).

In this paper, we purposefully omitted discussing the issue of ethics in QT, which would have further complicated the topic of different theories of democracy in the context of democratization. We acknowledge that there is a sprouting literature (Kop 2021, Perrier 2021a, 2021b, Meyer *et al* 2022) and a series of community-based efforts[145] on the topic and would encourage the interested readers to get involved with that fascinating and important topic. Similarly, literature on governance of QT has been emerging (Johnson 2019, Coates *et al* 2022), even intersecting with discussions on democratization (Kop 2021). Exploration of the relations between these concepts are intriguing avenues of research for further studies.

It has been argued that ‘society is promised new (quantum) technologies’ and that ‘it will get some, although they will not be things that will be understood by the broad midsection of society’ (DiVincenzo 2017, p 248). We believe that taking a step back and investigating how connecting the promises of QT with this broad midsection can yield valuable insights. QT has a role in the future of our societies, but it is up to all of us to deliberate on what that role is.

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Article 2.2: Communities of quantum technologies: Stakeholder identification, legitimation and interaction[146]

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This paper focuses on stakeholder identification as per the value sensitive design (VSD) approach applied to the context of quantum technologies (QT) and contributes to a better understanding of the complex and dynamic nature of the QT landscape. We pro- vide two comprehensive lists of stakeholders as starting points for VSD researchers and practitioners. These lists encompass a diverse range of organizations, including private companies, government agencies, NGOs, partnerships and professional/trade organizations. Our aim is to facilitate the recognition, legitimation and understanding of stake- holder interactions in the development of QT. These stakeholder lists lay a foundation for designing and implementing policies and strategies that promote the ethical and responsible development of QT, considering the values and interests of various stake- holders. Furthermore, these lists enable empirical and technical studies on specific QT innovations using an ethics-by-design approach like VSD.

Keywords: Stakeholders; quantum technologies; quantum computing; value sensitive design.

1. Introduction

Numerous industries, including healthcare, banking, energy and others, stand to benefit from quantum technologies (QT). QT refer to a spectrum of innovations and tools developed based on the principles of quantum mechanics. At the core, they leverage the unique behaviors of particles at the quantum level, such as superposition (where a quantum system can exist in multiple states simultane- ously) and entanglement (where particles become interlinked and the state of one instantly affects the state of the other, regardless of distance). These technologies include but are not limited to:

- Quantum Computing which exploits quantum principles to process information in ways that classical computers cannot, offering potentially exponential speed- ups for certain computational problems.
- Quantum Communication, where quantum mechanics is used to secure communication, is a notable example of quantum key distribution ensuring the secrecy of transmitted information.
- Quantum Sensing, Metrology and Imaging encompass a range of technologies that leverage quantum principles to push the boundaries of accuracy and sensitivity in various fields. Quantum Sensing and Metrology utilize quantum principles to develop

[146] https://www.worldscientific.com/doi/10.1142/S0219749924500126

sensors with unparalleled accuracy, applicable in areas such as gravitational wave detection and precision time-keeping. Simultaneously, Quantum Imaging employs quantum properties like entanglement to devise imaging techniques that transcend classical limits, further expanding the potential of QT in diverse applications.

QT have a plethora of possible uses, from developing novel materials to more effective batteries,[13] enhancing medicine discovery,[14] and transforming cryptography.[9] The number of businesses engaged in the development of QT is increasing along with the field.[7] These organizations originate from a variety of industries, including private businesses, governmental institutions, nongovernmental organizations, partnerships and professional/trade associations. Each has its own objectives and ideals. For understanding and guiding the development of QT it is important to comprehend who these organizations are, how they interact and what their individual responsibilities are in the QT environment. The ethical and responsible development of QT can be augmented by identifying stakeholders, validating their interests and figuring out how they interact.[12] This is done while taking into account the values and interests of various stakeholders.

In order to investigate the goals, formation and motivations of the numerous organizations working in the field of QT, this paper provides a classificatory matrix of the various organizations currently engaging in QT research and innovation. This article offers insights into the various stakeholder roles and responsibilities in the development of QT to help facilitate researchers to determine how their interactions can influence the field's future, using tools and insights from the value sensitive design (VSD) approach. In employing the VSD approach, we conduct a conceptual investigation — a key component of VSD that involves a philosophically informed analysis of the central constructs and issues under investigation. This type of investigation explicitly addresses questions such as "What are values?", "Whose values are impacted by QT?" and "How are these values supported or diminished by specific technological designs?". It allows us to engage in a detailed examination of the underlying values of different stakeholders without yet committing to extensive empirical analyses. By focusing on conceptual clarity, we establish a foundation for comparing results across research teams and setting a basis for the coherent development of policies.

At a cursory glance, the technological landscape might be replete with usual stakeholders. However, the uniqueness of QT necessitates a fresh perspective. Beyond the fascinating science, there's an intricate web of organizations, objectives and ideals. The stakes are high, and these entities' values can be the bedrock on which QT thrives or the hurdles that stifle innovation. The results of this study provide a conceptual investigation of the complex and dynamic nature of the QT environment, which can be used in further empirical investigations to determine important stakeholder engagement and collaboration dynamics that will shape the development of those systems. Following VSD principles, our identification of stake- holders in QT is rooted in a conceptual investigation. We critically examine how various stakeholder groups, including both direct and indirect stakeholders, are socially impacted by technological designs. This analysis has informed our classifi- cation of stakeholders, focusing on their values and how QT might affect them. By delineating these roles and responsibilities, we provide a

nuanced framework that aids in understanding the multifaceted interactions within the QT ecosystem.

Few studies [27,40] have performed a thorough examination of the various organi- zations involved in the development of QT despite the rising body of research on the ethical, social, and legal implications of these technologies (e.g. see Refs. 18, 19, 26 and 38). By providing a conceptual investigation of for-profit businesses, governmental organizations, nongovernmental organizations, partnerships and trade associations active in QT, this work adds to the body of literature.

This study offers insights into the various stakeholders influencing the development of QT by examining the goals, formation, purposes and values of these organizations. Additionally, by taking into account the values and interests of stake- holders, the VSD approach utilized to identify these stakeholders in this paper can assist in creating policies and strategies that support the ethical and responsible development of QT. As a result, this research contributes usefully to the literature by emphasizing the significance of stakeholder involvement and cooperation in determining the course of QT.[34] While this paper is framed within the VSD approach for identifying and engaging QT stakeholders, the insights provided are not confined to VSD practitioners alone. The classification matrix and the discussion of stakeholder roles and responsibilities are tools that can be applied in vari- ous contexts, informing a wide audience interested in the responsible development of QT.

In order to do this, this paper is organized in the following way. In the next section, we outline the various theoretical tools that emerge from VSD that are apt to identify the various stakeholders, legitimate[147] them, and determine how they interact with one another in potentially meaningful ways. Section 3 lays out the methodology used in this study to classify the numerous organizations involved in QT research and innovation. Section 4 provides some initial insights given this classification project, detailing how further conceptual as well as empirical investigations can benefit from this preliminary stakeholder identification. Section 5 discusses some of the limitations of this research and potentially fruitful avenues for further investigation. The final section provides conclusions.

2. Tools for Stakeholder Identification, Legitimation and Interaction

The VSD method is a framework for creating technologies that are aligned with and embody stakeholders' values and interests. The approach acknowledges that the creation of new technologies is not value-neutral and that these developments may have both intentional and unforeseen effects on people, organizations and society as a whole. In order to make sure that technologies reflect users' beliefs, interests and needs, VSD aims to involve stakeholders in the design process.

[147] Legitimation, in the context of stakeholder identification, refers to the process of acknowledging, validating, and justifying the relevance and importance of various stakeholders in a given domain or field. This process not only recognizes the existence and roles of stakeholders but also endorses their rightful place in the discussion, decision-making and development processes. It involves an understanding of the interrelationships, power dynamics and value propositions of different entities, ensuring that their voices and interests are appropriately represented and considered.

In the 1990s, Friedman et al. created the VSD approach.[10] They understood that the design process for developing technologies needed to be more sensitive to the requirements and values of stakeholders because it was common for these technologies to be developed without taking ethical, social, or environmental concerns into account. They argued that in order to better understand stakeholders' beliefs and incorporate them into the design process, designers needed to interact with them. For this reason, the VSD approach to technology development is crucially dependent on stakeholder *identification, legitimation* and *interaction* tools which fall under the rubric of conceptual investigations, one of the three main phases of any VSD application. Identification of all parties with an interest or stake in the development of the technology, as well as those who may be impacted by it, is known as stakeholder analysis.[11,23] This technique enables designers to comprehend the variety of viewpoints and interests that could affect the technology's conception, application and use. This article engages in a conceptual investigation as per VSD, where we delve into the philosophical underpinnings of stakeholder values. This approach, distinct from empirical analyses, offers a structured exploration of how the design and use of quantum technologies can affect stakeholders both directly and indirectly.

After stakeholders have been identified, legitimation strategies are employed to guarantee that their interests are regarded as valuable and genuine during the development process.1 By highlighting the significance of stakeholders and their connections to the technology, the stakeholder analysis tool, for instance, is a potent means to legitimize stakeholder interests. Prioritizing which stakeholders in the develop- ment process should receive greater attention or resources can also be helpful.

Then, interaction tools are employed to encourage stakeholder engagement and communication. One such tool is the stakeholder tokens tool. According to Yoo,[42] the stakeholder tokens tool provides a tangible or digital representation of individual stakeholders or stakeholder groups. These tokens can be used in collaborative settings such as workshops, brainstorming sessions, or decision-making meetings. Stakeholder tokens offer a mechanism to track and record stakeholder contributions over time, ensuring that a comprehensive record of their inputs, concerns and suggestions is maintained. Additionally, these tokens serve as an avenue for stake- holders to express their values, opinions, interests and preferences, thus promoting transparency, inclusivity and active participation in the development process.

QT can be developed in ways that are in line with the significant values of stakeholders by using the VSD approach and its accompanying tools. More broadly speaking, VSD can be used in at least the following ways concerning QT:

- *Identification of stakeholders:* It is crucial to identify all parties who could be impacted by the development of QT, including investors, users, regulators and advocacy groups. To make sure that these stakeholders' viewpoints are taken into account during the design process, VSD can help identify these stakeholders and their interests. In this study, we will primarily focus on the question of how to formulate a core list of relevant stakeholders. This often takes on the form of a literature review to create a preliminary list of stakeholders that is then revised given subsequent empirical investigations.

- *Stakeholder legitimation:* When stakeholders have been identified, VSD can be used to validate their viewpoints and interests. The stakeholder analysis tool, for instance, can assist developers in determining the significance of various stakeholders and their connections to the technology (cf., Ref. 43). This can make sure that during the design process, the interests of all stakeholders are taken into consideration.
- *Stakeholder interaction:* Due to the complexity of QT, a number of stakeholders with various specialities may need to work together. By the use of tools like stakeholder tokens, VSD may assist in fostering collaboration and communication between stakeholders. This tool can aid in organizing and facilitating stakeholder interactions, making sure that everyone involved has the chance to voice their opinions (cf., Ref. 17).
- *Values:* QTs have the potential to have a big impact on society, including ethical, societal and environmental issues.[5,31] To make sure that these values are taken into account during the design process, VSD can be used to identify and prioritize them. For instance, ethical problems with the collecting and use of private information in quantum sensing can be found using VSD.

3. QT Stakeholders in the literature

The emerging literature on the ethical, legal and societal aspects (ELSA) already discuss to some extent the role of stakeholders in the development of QT. In this section, we survey this literature, collecting the presented views on the identification, legitimation of and interaction with stakeholders.

3.1. Literature search method

To identify the relevant literature, we initially adopted a bibliometric approach,[21] utilizing the Scopus database with the following query[148] on 10 October 2022 and ended up with 11 articles. After reading the abstracts of each article, we only found five of them to be relevant to QT. Next, we tried relaxing the query conditions by removing the “AND (“responsib*” OR “stakeholder*”)” part. This led to 160 articles; however, a majority of these articles were technical papers, mainly on quantum key distribution due to the keyword “legal” being used in a different context. Removing this keyword reduced the results to 53, and after reading the titles and abstracts, we identified 15 of them as relevant literature.[149] From previous literature,[41] we knew that there should be somewhere around at least 20 articles. At this point, we ran co-citation and bibliographic coupling analysis on the 15 articles we have, which identifies articles that were cited by multiple articles in our dataset, and which articles were cited together in the references section of the articles in our dataset. This led to the identification of four more relevant articles. At this point, we checked the list and realized that some papers known by the authors are not present in the list.

[148] Query: ((“quantum tech*” OR “quantum comput*” OR “quantum sensing” OR “quantum sen- sor*” OR “quantum simulation” OR “quantum cryptograph*” OR “quantum communication”) AND (“ethic*” OR “legal” OR “societal”)) AND (“responsib*” OR “stakeholder*”).

[149] We searched for the terms “ethic*” and “responsib*”, and selected those papers that employ these words in a meaningful manner, not just a mere passing mention or used in a different context (especially for the term “responsib*”).

Next, we manually investigated the references sections of the papers at hand and also the articles known by the authors. We realized two key points: (i) some of the articles were published in new journals, meaning they couldn't be discovered via a Web of Science (WoS) or Scopus literature research because the journal is not indexed yet (one example is the journal *Digital Society*, which published its first issue in July 2022), (ii) any attempt to cover all the ELSA keywords together with relevant quantum keywords would eventually lead to orders of magnitude more false positives than true positives, this is mainly due to the difference in the size of literature in QT versus the ELSA of QT. The QT literature has more than 84.000 scholarly works in Scopus-indexed journals (utilizing the keyword from Ref. 35), while ELSA of QT has less than 50.

After all the steps above, we ended up with a list of 39 scholarly works indexed by Scopus. Next, we downloaded each paper/book and ran searches for keywords "Responsib*" and "Ethic*", and read the paragraphs and sections to identify in which contexts these words were present in the text. We identified 18 from the list containing the concept of responsibility/responsible, and 19 contained the concept ethics/ethical in the contexts we were aiming for, 14 of the concepts contained both works. Therefore, we focused our attention on these 14. In each, we searched for the keyword "stakeholder" and highlighted the relevant section. Our highlights of these sections and the following takeaway messages are below, provided in chronological order depending on the publication years. The summary of the information on these articles can be found in Table 1.

Table 1: Title, in-text citation, year, and link to the publication for the 14 articles identified.

Title of the article	**In-text citation**	**Year**	**Link to publication**
Quantum Technologies and Society: Towards a Different Spin	(Coenen, et al., 2021)	2022	https://doi.org/10.1007/s11569-021-00409-4
Auditing the 'Social' of Quantum Technologies: A Scoping Review	(Wolbring, 2022)	2022	https://www.mdpi.com/2075-4698/12/2/41
Ethics education in the quantum information science classroom: Exploring attitudes, barriers, and opportunities	(Meyer, et al. 2022)	2022	https://arxiv.org/abs/2202.01849
Quantum technology and human rights: an agenda for collaboration	(Krishnamurthy, 2022)	2022	https://iopscience.iop.org/article/10.1088/2058-9565/ac81e7
Q-turn: changing paradigms in quantum science	(Sainz, 2022)	2022	https://iopscience.iop.org/article/10.1088/2058-9565/ac82c4
Intellectual property in quantum computing and market power: a theoretical discussion and empirical analysis	(Kop, et al. 2022)	2022	https://doi.org/10.1093/jiplp/jpac060
Digital justice in 2058: Trusting our survival to artificial intelligence, quantum	(Ritter, 2021)	2021	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=

Title of the article	In-text citation	Year	Link to publication
and the rule of law			3778678
Reading the road: challenges and opportunities on the path to responsible innovation in quantum computing	(Ten Holter, et al., 2021)	2021	https://www.tandfonline.com/doi/full/10.1080/09537325.2021.1988070
Asleep at the wheel? Responsible Innovation in quantum	(Inglesant, et al., 2021)	2021	https://www.tandfonline.com/doi/full/10.1080/09537325.2021.1988557
Talking about public good for the second quantum revolution: analysing quantum technology narratives in the context of national strategies	(Roberson, et al., 2021)	2021	https://doi.org/10.1088/2058-9565/abc5ab
The Potential Impact of Quantum Computers on Society	(de Wolf, 2017)	2017	https://link.springer.com/article/10.1007/s10676-017-9439-z
Responsible research and innovation (RRI) in quantum technology	(Coenen & Grunwald, 2017)	2017	https://link.springer.com/article/10.1007/s10676-017-9432-6
The societal impact of the emerging quantum technologies: a renewed urgency to make quantum theory understandable	(Vermaas, 2017)	2017	https://link.springer.com/article/10.1007/s10676-017-9429-1
Quantum computing and cloud computing: Humans trusting humans via machines	(Grodzinsky, et al., 2011)	2011	https://ieeexplore.ieee.org/document/7160598

3.2. Literature summary and general points

Vermaas[38] argues that for a societal debate on QT to be effective, stakeholders need to have a reasonable understanding of the technologies in question. Quan- tum theory is notoriously difficult to understand, but philosophers of physics can help provide stakeholders with the necessary understanding to participate in the debate. He suggests that current RRI approaches need to be expanded to include all stakeholders in the debate on QT. He also recommends organizing the debates in a manner which should distinguish between issues that arise during the transitional phase of introducing new QT and those that have a more permanent impact on society. By engaging in open dialogue and considering a range of perspectives, stakeholders can work together to guide the development of QT in a direction that is beneficial for all.

Coenen and Grunwald[5] propose the implementation of a “strong” RRI approach to ensure the responsible development and commercial viability of QT. This approach involves linking core policy processes to stakeholder dialogues, decision- supporting public engagement and a wide variety of other public communication activities. The authors emphasize the importance of

engaging with a wide range of stakeholders at an early stage, including industry, early adopters and key stakeholders, as well as the general public, in order to ensure that the development of QT aligns with societal values and interests. They also stress the need for proactive engagement with stakeholders throughout the lifecycle of QT, not just closer to the market. They caution against using uncertainties surrounding QT as an excuse to delay or avoid dialogue, as this could allow others to shape the narrative in unhelpful ways. Instead, the authors advocate for mutually informative dialogue with all stakeholders to give a broader picture of public perception and foster a shared narrative that is widely recognized and welcomed. In summary, Coenen and Grunwald[5] argue for a societal debate on QT that involve open dialogue and consideration of a range of perspectives. This can help guide the development of QT in a direction that is beneficial for all and ensure that the research delivers results that are socially desirable and undertaken in the public interest, while helping to avoid large parts of the general public learning about QT via unfounded and potentially frightening speculations.

Roberson et al.[30] argue that the concept of "public good" in research should focus on the diversity of stakeholders and their engagement to ensure that research outcomes benefit society as a whole. The authors propose a "public good test" that includes three elements: research agendas, social orders and research-society networks. These elements should be diverse to pre-empt narrow outcomes that may harm certain groups, and stakeholders should be involved in exploring different agendas and outcomes. In their article, they emphasize that research funding, insti- tutions of research utilization and public communication of science play a crucial role in shaping research's capacity to address the public good for all stakeholders.

Holter et al.[37] argue that responsible innovation (RI) requires engagement with stakeholders in the development of QT. Their case studies suggest that identify- ing stakeholders is not limited to ultimate users but also includes peers within the research team and similar fields. In their article, they also emphasize the importance of managing expectations and representing QT in a non-hyperbolic way to stake- holders, including funders and policymakers as well as the general public. Widening the pool of stakeholders consulted is necessary to develop a better understanding of the possible effects and impacts of quantum-based technologies. Engagement should not only happen with the public but with all interested stakeholders, including regulators, contingent industries and other branches of the academy. Overall, their work emphasizes that identifying and engaging with stakeholders is critical for developing and implementing QT responsibly.

Wolbring[41] argues that involving stakeholders is crucial in building literacy in the societal impacts of QT. Some quantum policy documents indicate the need to involve stakeholders in reviewing the potential impacts of QT on society,[28,40] and some countries have already carried out public consultations on their quantum strategies.[3] Since QT research is still a relatively recent topic for many governments, the discussion among stakeholders is still ongoing, and several European countries have yet to develop social, ethical and legal parameters.[28] Wolbring suggests that mapping out the "social" within a differentiated map of the applications allows for social risk to be mapped out in a meaningful way as well as to build literacy in the societal implications. He argues that a mapping exercise could also be used as a pedagogical tool in EDI curricula content and other courses, engaging with the concept of stakeholder and citizen engagement in

society. He highlights the importance of involving stakeholders and building their understanding of QT to support meaningful societal debate and decision-making.

Ritter[29] highlights the rarity of open dialogue among technology and legal stakeholders regarding how to innovate and govern. Krishnamurthy[20] stresses how governments can create the conditions for successful self-regulatory and multi- stakeholder initiatives in order to address the human rights impacts of QT. Finally, Meyer et al.[22] point out that QIS researchers and stakeholders from technical back- grounds, although accepting that ethical issues undeniably emerge in QT, they believe these issues do not diverge significantly from those of other areas of engi- neering and technology and are perhaps better suited for philosophy departments rather than the public domain.

In summary, from the previous literature in the articles published in Scopus-indexed journals, we can list the following points to be taken into account when getting involved in stakeholder identification and engagement:

- Involving stakeholders in reviewing the potential impacts of QT on society to support meaningful societal debate and decision-making.
- Mapping out the “social” within a differentiated map of the applications to allow for social risk to be mapped out in a meaningful way, build literacy in the societal implications, and be used as a pedagogical tool in EDI curricula content and other courses.
- Providing stakeholders with a reasonable understanding of the technologies in question through engagement with philosophers of physics and open dialogue that considers a range of perspectives.
- Implementing a “strong” RRI approach that involves engaging with a wide range of stakeholders at an early stage and throughout the lifecycle of QT to ensure the development aligns with societal values and interests.
- Focusing on the diversity of stakeholders and their engagement to ensure research outcomes benefit society as a whole through a “public good test” that includes research agendas, social orders and research-society networks.
- Engaging with stakeholders, including peers within the research team and similar fields, regulators, contingent industries and other branches of the academy, to develop a better understanding of the possible effects and impacts of quantum- based technologies.
- Managing expectations and representing QT in a non-hyperbolic way to stake- holders, including funders and policymakers as well as the general public.
- Collaboration between certain stakeholder groups are seen as more important or necessary by some authors, the role of governments as facilitators is stressed upon and no consensus on where discussions on ethical issues arising from QT should be tackled is hard to locate.

Further condensing these points raised in the literature into the basis of a framework for identifying, legitimating and interacting with QT stakeholders, we identified the following elements covered in the literature:

1. **Early and continuous engagement:** Implement an RRI approach that involves diverse stakeholders throughout the lifecycle of QT, ensuring align- ment with societal values and interests.
2. **Stakeholder literacy and social impact mapping:** Provide stakeholders with a reasonable understanding of QT, manage expectations and create a differentiated map of QT applications to identify social risks and build societal implications literacy.
3. **Inclusive engagement and collaboration:** Encourage collaboration across sectors and emphasize the role of governments as facilitators in the stakeholder engagement process, fostering a comprehensive understanding of QT impacts and addressing ethical issues.

3.3. Ethical orientations and interests of stakeholders in QT

Understanding the roles and interests of stakeholders is foundational. However, to create a comprehensive framework that addresses both stakeholder identification and ethical considerations, we must dive into the ethical orientations, interests and potential conflicts that stakeholders might harbor regarding QT.

- **Industry players:** These stakeholders primarily aim for technological advance- ment and commercial viability. However, their interests might sometimes prioritize profit over broader societal benefits, leading to ethical concerns like data privacy, monopolization, or the rapid deployment of under-tested technologies. While industry players are essential for technological advancement, their primary focus on commercial viability may at times conflict with the broader societal values, such as privacy and equity. This tension highlights a potential area of conflict, particularly when profit motives might overshadow ethical considerations. Such scenarios underscore the need for a vigilant regulatory framework that ensures the alignment of QT development with societal values.
- **General public:** Their ethical concerns center around the direct and indirect effects of QT on daily life. This includes potential surveillance concerns, implications for employment (like job losses due to automation), and the societal consequences of major technological shifts.
- **Government bodies:** While they aim to foster innovation, they must also pro- tect citizens from potential harm. Ethically, their position is often a balancing act between facilitating technological growth and ensuring societal safety and equity.
- **Research teams and academia:** Their primary objective is knowledge expan- sion. Ethical concerns for this group include ensuring research integrity, avoiding hyperbolic claims and considering the broader societal implications of their find- ings, beyond just the academic realm.
- **Early adopters:** They are often excited about the possibilities of new technologies. However, their enthusiasm might overlook potential ethical pitfalls, such as adopting systems that might later prove to have privacy concerns or other unintended consequences.
- **Regulators:** They play a crucial role in creating a safe landscape for QT deployment. Their ethical considerations revolve around ensuring that new regulations protect society without stifling innovation. Regulators are pivotal in managing the complex dynamics between innovation and societal welfare. Their role often involves navigating the

conflicting interests of various stakeholders, including reconciling the industry's drive for rapid technological deployment with the public's need for thorough vetting of new technologies for safety and privacy concerns. This positions regulators as key mediators in potential conflicts, emphasizing their significant influence on the responsible evolution of QT.

By examining these ethical orientations, we can identify potential conflicts. For instance, industry players might be in disagreement with regulators about the speed at which a new QT should be rolled out. Philosophers of physics might challenge research teams on their claims about the potential of QT, advocating for more grounded and realistic public communications. Understanding these ethical positions is crucial not just for effective stakeholder engagement, but also for anticipating potential challenges and conflicts as QT continues to evolve and permeate society. Future research should focus on developing strategies and frameworks to navigate these ethical concerns, ensuring a holistic and responsible advancement of QT.

In the following section, we delve into the topic of identification of stakeholder groups that are directly or indirectly affected by the development and deployment of QT. By identifying the wide diversity of the stakeholder groups, we aim to emphasize the necessity of a multi-faceted approach to address the diverse range of ethical, social and environmental issues that arise from the development and implementation of QT.

4. QT Stakeholder Communities

4.1. Existing listings of stakeholders

In the relevant literature, only a few studies exist that explicitly emphasize who these stakeholders are. One such study is the WEF Quantum Computing Gover- nance Principles. Authors identify seven key stakeholders in their report (Ref. 40, p. 7); (i) governments, (ii) academics and universities, (iii) international organizations, (iv) corporations and private entities that are using the technology, (v) corporations and private entities that are developing the technology, (vi) developers (individuals) and (vii) consumers (individuals). Another study, focusing on the quantum gover- nance stack (Ref. 27, p. 2) identifies again seven key stakeholder groups; (i) states (governments) as the primary agents of regulation and their role in (a) international and (b) national formal (legislative) regulation; (ii) multilateral institution(s); (iii) national instrumentalities, such as parliaments and administrative agencies; (iv) industrial and commercial stakeholders; (v) universities and academia; (vi) indi- vidual producers/consumers of QT and (vii) civil society and technical community groups. A different study focusing on the needs of the quantum industry (Ref. 16, p. 2) identifies five stakeholders; (i) students, (ii) university educators and admin- istrators, (iii) policy makers, (iv) funding agencies and (v) quantum companies. One final study that explicitly focuses on the list of stakeholders is a study con- ducted in the context of QT outreach and education,[36] where the stakeholders are asked to be identified and ranked by participants of the study. The resulting list contains (i) universities, (ii) research institutions, (iii) scientific associations, (iv) science centers, (v) high schools, (vi) companies/industry, (vii) student associations, (viii) museums, (ix) secondary schools, (x) professional associations, (xi) nonformal educational bodies, (xii) local communities and (xiii) municipalities. These already extensive lists still omit some key stakeholders, such as investors,

media and journalists and affected communities, among possibly others, either by omission or counting them under other categories (like civil society or industry).

Acknowledging that identifying stakeholders can be a challenging process is crucial for a more comprehensive understanding of the QT ecosystem. These studies provide a starting point, but the omission of certain obvious stakeholders highlights the complexity of this task. The dynamic nature of technology and its societal impacts requires continuous reassessment and adaptation of stakeholder lists to ensure inclusivity and effective collaboration. By recognizing the inherent difficulties in stakeholder identification and striving for a more encompassing approach, we can better address the multifaceted concerns and opportunities that arise in the development and application of QT.

Furthermore, stakeholder identification relies heavily on the context and the aimed model. A good example of this can be observed in a detailed previous work[27] covering also the duties and rights-based approach of quantum governance. Stakeholder identification and engagement are explicitly included in this model (Ref. 27, pp. 12–13), and an extensive table titled Quantum governance stack (Ref. 27, p. 41) with a detailed matrix for different quantum stakeholders versus types of governance instruments, denoting the category, agents, objectives/risks, instruments, rights/interests, powers/duties and an example for each stakeholder can be found. However, media and journalists are only mentioned in this framework once (Ref. 27, p. 37) and only as civil society stakeholders in their relation to setting agendas, high- lighting risks, and drawing attention to issues requiring governance responses, as the model prioritizes governance-related relations over others. Different contexts and models highlight and constraint the roles and significance of potential stakeholder configurations.

4.2. Stakeholder identification

In the context of VSD, a stakeholder can be defined as any individual, group, or entity that has a direct or indirect interest in, is affected by, or can influence the design, development and use of technology, considering its ethical, social and environmental implications.[2,12,23] As is typical in VSD conceptual investigations, we adopt both extant stakeholder groups that have previously been identified in the literature as well as ones that may be particular to QT more specifically. Such categorizations are then revised in light of subsequent empirical investigations. Although our methodology is inspired by VSD, it offers a structured classification that can be utilized beyond the immediate scope of VSD. This versatility allows for broader application in stakeholder analysis within QT development, potentially serving as a tool for those not exclusively using the VSD framework. It is our intention that the methodologies and insights presented here, while emerging from a VSD perspective, will also be valuable to a wider audience concerned with the ethical and responsible advancement of QT. A revised list of stakeholders with their roles and significance highlighted, and with the reasoning for including them, is given in Table 2.

Table 2: Stakeholder groups, their role and significance, and the reasoning behind including them.

Stakeholder Group	**Role and Significance**	**Reasoning**
Researchers and developers	Individuals and organizations directly involved in the creation and advancement of QT; responsible for aligning their work with ethical, social, and environmental considerations.	Their work shapes the technology's design and development, and they need to consider the ethical, social, and environmental implications of their work to align with the values of other stakeholders.
Educators and training providers	Individuals and institutions responsible for teaching and training students, researchers, and professionals in the field of quantum technology. Their role is essential in building a skilled workforce that understands the ethical, social, and environmental implications of quantum technology development and use.	They are vital stakeholders because they shape the knowledge, skills, and values of future quantum technology professionals. Their expertise aids in designing effective educational programs and resources, ensuring preparedness to address complex challenges. In the context of VSD, their influence on ethical considerations makes their inclusion in decision-making processes crucial.
End-users and adopters	Individuals or organizations utilizing QT in various fields; their experiences, values, and needs must be considered for useful and responsible technology development.	They are affected by the design and functionality of QT, and their experiences, values, and needs must be taken into account to ensure the technology is useful and responsible.
Regulators and policymakers	Governmental entities creating laws, regulations, and policies governing QT development and use; responsible for protecting public welfare and promoting responsible innovation.	They have the responsibility to ensure that QT is developed and used in a way that aligns with society's values and interests, protecting public welfare and promoting responsible innovation.
Investors and funders	Public and private funding sources for QT research, development, and commercialization; influence the direction and focus of QT development and ensure alignment with societal values.	Their financial support influences the direction and focus of QT development, and they have an interest in ensuring that the technology is developed responsibly and provides a return on investment that aligns with societal values.

Industry partners and suppliers	Companies and organizations providing resources, infrastructure, or expertise to support QT development; their involvement can influence the design, availability, and adoption of the technology.	Their involvement in the QT ecosystem can influence the design, availability, and adoption of the technology, and their values and interests should be considered in the development process.
Ethics and societal experts	Individuals and groups focusing on ethical, social, and legal aspects of QT; help identify, analyze, and address potential implications of QT to ensure alignment with societal values.	They help identify, analyze, and address potential ethical, social, and legal implications of QT, ensuring that the technology is developed and used in a manner consistent with societal values.
General public and affected communities	Wider society and specific communities impacted by QT development and applications; their values, concerns, and potential should be considered for responsible and inclusive technology development.	They have a stake in how QT is developed and used, as it may impact their lives, environment, or social structures. Their values, concerns, and potential benefits should be considered throughout the design process to ensure responsible and inclusive technology development.
Media and journalists	Professionals communicating news, updates, and critical analysis of QT to the public; facilitating dialogue and raising awareness of QT's implications and potential impact on society.	They play a crucial role in shaping public opinion, raising concerns, and generating constructive discussions that can guide the development and use of QT in a way that aligns with societal values. By accurately and responsibly reporting on QT, they help ensure that the wider public stays informed and engaged with the technology's progress and ethical considerations.

While the list provided offers a comprehensive overview of the main stakeholders in the QT domain from a VSD perspective, it is essential to acknowledge that the landscape of stakeholders can evolve over time, and the identification of stakeholders highly depends on the context. New stakeholders may emerge, and the roles and interests of existing stakeholders may change as QT develops and becomes more integrated into society. Moreover, it is challenging to create an exhaustive list of stakeholders that captures every individual or group with a potential interest in or who may be impacted by QT. Therefore, it is important to continually reassess and update the list of stakeholders as the field advances and new insights emerge.[150] For this reason, conceptual investigations like this remain iterative, reformulating as novel and potentially conflicting empirical data is considered.

[150] A foundational precept of the VSD is exactly the point of the dynamic nature of society and technology, and, as a result, any design project should be open to continual reevaluation.[12]

As an example of the way the list can be constructed differently, one can argue that educators and training providers could be considered as part of (a) Researchers and developers, as they are often involved in academic institutions, and research organizations responsible for the creation and advancement of QT. Although they play a crucial role in educating and training the next generation of professionals in the field, they are traditionally considered a subgroup under academics as academics and industry R&D teams handle most emerging technologies-related education and training. However, it is possible to emphasize their role separately by including them as an additional stakeholder category, as in the QT community, there are many global education and training programs that cannot be classified as a subgroup of researchers and developers.

4.3. Stakeholder sampling

There is limited literature specifically addressing stakeholder sampling in the context of VSD. However, stakeholder sampling can be informed by general principles and strategies found in many other resources which aligns with VSDs commitment to adopting best practices of extant methodologies. For the purpose of this work, we introduce three widely utilized and adopted sampling strategies [4] which are snow- ball, maximum variation and purposive sampling. A summary of the strategies and their respective shortcomings for VSD purposes can be found in Table 3.

These shortcomings can be overcome by using a combination of sampling strategies, tailored to the specific context and goals of the specific VSD research at hand. By employing a mixed-methods approach, VSD practitioners can leverage the strengths of each strategy while minimizing their limitations. One such path could be to start with purposive sampling to ensure that a wide range of stakeholder perspectives and expertise are included. This will help address potential bias by selecting individuals or groups that the researcher believes will bring valu- able insight into the study. The following step can be the use of maximum variation sampling to further diversify the sample and ensure that both majority and minority viewpoints are represented. This will help to reduce the risk of overlooking less common or less connected perspectives (Ref. 25, pp. 234–235). Finally, employing snowball sampling as a third step can expand the sample and uncover additional stakeholders who might have been missed in the initial selection process. This will help to ensure that the study includes a broader network of stakeholders and captures a more comprehensive range of opinions, experiences and values. By combining these sampling strategies in a systematic way, practitioners can create a more robust and representative sample of stakeholders, ultimately enhancing the validity and relevance of the VSD research for their respective fields of QT.

One caveat here might be also to emphasize when a stakeholder belongs to multiple groups. It is essential to recognize and address the multifaceted roles and interests of such stakeholders. One approach is to create a distinct category that captures their unique combination of roles and explains how this combination influences their perspective on the technology. Alternatively, one could mention their multiple affiliations within the stakeholder descriptions, clarifying their diverse connections and contributions to the technology’s development and application. Acknowledging these overlapping roles will help ensure that they are not reduced to a single role.

Table 3: Sampling strategies and their shortcomings

Sampling strategy	Description	Shortcoming
Snowball	Initial stakeholders are asked to recommend additional stakeholders to involve in the process. This approach can help to identify stakeholders who may not have been initially recognized but have valuable insights and perspectives to offer.	May result in a biased sample, as stakeholders who are already connected or share similar perspectives are more likely to be included, potentially overlooking less connected or minority viewpoints.
Maximum variation	Aims to include stakeholders representing the widest possible range of perspectives and experiences. It helps to capture diverse viewpoints and identify common patterns across different stakeholder groups.	May limit the depth of understanding in VSD research, as it focuses on including diverse stakeholder perspectives, but might not fully explore each stakeholder's nuanced opinions, values, or experiences in detail.
Purposive	Involves selecting stakeholders based on specific criteria relevant to the VSD process, such as expertise, demographics, or roles within an organization. This approach can help to ensure that stakeholders with the necessary knowledge and experience are included in the VSD process.	May be subject to researcher bias, as the selection of stakeholders is based on the researcher's judgment, which can inadvertently exclude important perspectives or fail to represent the full range of stakeholder values and concerns.

4.4. A stakeholder search

For researchers and practitioners aiming to work on VSD for QT, we have generated two lists of potential stakeholders and access points for them to utilize in their projects. Please note, as mentioned above, it is essential to acknowledge that the landscape of stakeholders can evolve over time, and the identification of stakehold- ers highly depends on the context. New stakeholders may emerge, and the roles and interests of existing stakeholders may change. That being said, our list of stakehold- ers provides a good starting point for those aiming to follow the three-step sampling process of purposive, maximum variation and snowball strategies.

In line with typical VSD conceptual analyses concerning stakeholder identification, the first dataset we present consists of results obtained by analyzing the 76,724 publications selected from the WoS core collection utilizing a search query (see Appendix A) previously utilized in the literature[32] on 6 April 2023. Anyone with access to the WoS interface can re-run our query and obtain an updated version of our dataset. But for those that do not want to take that route, our dataset can be accessed via.[35] The details on the content of our dataset are listed in Table 4.

Table 4: Information on the contents of our dataset obtained from the WoS Core Collection

Type of data	**Number of entries**
Affiliations	772
Funding agencies	256
Conference titles	120
Grant numbers	184
Publication titles	179
Publishers	54

For all the data types, except conference titles, we selected the cut-off point as 50, meaning that only affiliations, funding agencies, grant numbers, publication titles and publisher with at least 50 publications out of the 76,724 publications selected from the WoS core collection via the query. For conference titles, the cut-off point was selected as 15, due to the low number of entries per conference title in the dataset. These cut-off points are rather arbitrary but beneficial in cutting the numbers down into manageable and meaningful sizes for their potential uses in stakeholder sampling strategies. As mentioned above, any researcher or practitioner interested in the full set can re-run the search query on the WoS interface and obtain the full lists.

Table 5: Information on the contents of our Preliminary QT Stakeholders dataset

Type of data	**Number of entries**
NGOs/Communities	42
QT Start-ups and SMEs	460
Public Organisations	5
Venture Capital	127
Professional/Trade Association	5
Partnership/Consortia	14
Manifestos/reports	8
Major Companies involved in QT	19
ELSA Researchers	34
ELSA Groups	20
Media and journalists	5

In the following step, we embarked on a more manual process to create what we called a "Preliminary QT Stakeholders" list.[34] Initially, we aimed to follow previously formulated lists and categories in the literature, such as those found in Refs. 27 and 40, or as shown in Table 2. However, we encountered difficulty in assigning many of the stakeholders to just one category or even to any category at all. As a result, we opted to provide the raw list with our preliminary categorization, leaving the more detailed categorization (i.e. adapting this list to the specific context of a research question or project) to our audience and VSD designers engaging in empirical investigations. Our dataset also builds upon those found in the literature, such as Dargan8 for venture capital and Seskir et al.[33] for start-ups. Table 5 presents some details on the content of our second dataset.

Combining the information found in both datasets, summarized in Tables 4 and 5, researchers and practitioners of VSD can gain access to a comprehensive range of QT stakeholders. These datasets can also be used in conjunction with existing resources that focus on specific groups or subfields of QT. A list of such resources can be found in Table A.1. This integration offers interested parties a solid foundation and multiple options for implementing a mixed-methods approach to sampling strategies in their VSD applications.

4.5. Discussion on methodological approach

While our study provides an extensive list of stakeholders actively engaged in the QT realm, we acknowledge the methodological limitation of our work. By using the WoS core collection, we have predominantly captured stakeholders who are deeply and actively contributing to the QT literature. This method inherently leans towards stakeholders who are potentially very positive towards QT. It's crucial to note that while these active contributors play a significant role in shaping the QT landscape, they represent only one facet of the vast array of stakeholders affected by the rise of QT. Many stakeholders, especially those who might experience the broader societal, economic, or ethical impacts of QT, may not necessarily be publishing extensively on the topic but still hold significant stakes in its development and implications. The stakeholder classification, while derived from a VSD perspective, provides a versatile understanding of the QT landscape. This classification is relevant for policymakers, researchers and industry professionals who may not employ VSD but still require a comprehensive overview of stakeholders. It serves as a foundational tool for engaging a broader audience in the discourse on QT, facilitating a more inclusive and ethically responsible development of these technologies.

In considering these varied interests, ethical dilemmas, such as the trade-off between advancing QT and protecting individual privacy, are indicative of the underlying conflicts between stakeholders. Investors, for instance, may push for a swift rollout of new technologies to maximize returns, which can be at odds with the regulators' duty to ensure public safety and privacy. These dilemmas highlight areas that future research should explore, particularly in understanding how to reconcile the fast-paced growth of QT with the imperative to safeguard societal values. For a more comprehensive view, future research may consider integrating methods like surveys, interviews, or focus groups targeting sectors not represented in our dataset. Engaging in public discourse or hosting public forums could also shed light on concerns, values and interests of individuals and groups who are indirectly affected by QT. A

good example of this approach is the quantum technologies public dialogue report.[24] By combining insights from both active contributors and broader society, we can work towards a more holistic understanding of the QT stakeholder landscape, ensuring that its development is both inclusive and ethically responsible.

Furthermore, as our study primarily focuses on the identification of stakeholders, we recognize that exploring the complexities of their interactions and relationships is a subject for future research. This study's conceptual nature does not provide detailed guidance on operationalizing the stakeholder lists for specific VSD applications, but offers a sampling strategy as a starting point. We invite future research to refine these categorizations and conduct empirical studies to better understand stakeholder dynamics within the QT domain. The stakeholder lists provided, while comprehensive, may not be exhaustive. The rapidly evolving landscape of QT may result in the emergence of new stakeholders or changes in the roles of existing ones. Additionally, the categorization of stakeholders is based on our analysis and understanding, which may not perfectly align with every research context or project. Therefore, researchers and practitioners should be aware of these limitations and adapt the lists according to their specific needs and requirements. This is often the case in VSD applications where further empirical investigations are conducted to determine if conceptual investigations like the one conducted in this study are legitimate, and revisions often take place.

Second, our study focuses primarily on identifying stakeholders rather than delving into the complexities of their interactions and relationships. While this provides a valuable starting point, it leaves room for further exploration in under- standing how stakeholders engage with each other and collaborate in developing QT. Furthermore, as the study is conceptual, it does not provide detailed guidance on operationalizing the stakeholder lists for specific VSD applications. However, it details a sampling strategy as a tool for operationalizing this (or any) stakeholder list. Future research could address these limitations by refining categorizations, conducting empirical studies on stakeholder interactions and their implications and developing methodologies to integrate the stakeholder lists into the context of VSD more effectively. A host of tools form part of the VSD repertoire geared exactly toward these kinds of empirical investigations to determine better such interactions and their relevance to any given system design.[12]

5. Conclusions

In the rapidly evolving domain of QT, a nuanced understanding of the landscape is crucial. This article, grounded in the VSD methodology, particularly through conceptual investigations, aims to provide a foundational stakeholder list as a starting point for deeper engagement and alignment with societal values. We are aware, how- ever, that this list is part of a larger toolkit necessary for navigating the complex ethical and societal challenges QT presents. As a component of the VSD approach, this tool — one among many — must be leveraged alongside ongoing dialogue, empirical research and cross-sectoral collaboration to ethically and responsibly har- ness QT's potential. The stakeholder list, informed by conceptual investigations for stakeholder identification, serves as a preliminary guide to inform decision-making processes. This paper thus contributes to the broader conversation on QT development, encouraging further research and collaboration. As QT advances, we must refine our stakeholder engagement strategies and broaden our research methodolo- gies to address the field's societal implications adequately.

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Appendix

TS = ("quantum simulation" OR "quantum imaging" OR "quantum sensing" OR "quantum sensor" OR "quantum computation" OR "quantum computing" OR "quantum computer" OR "quantum coding" OR "quantum programming" OR "quantum error correction" OR "quantum error correcting" OR "quantum circuits" OR "quantum algorithm" OR "quantum algorithms" OR "quantum network" OR "quantum networks" OR "quantum channel" OR "quantum channels" OR "quantum cryptology" OR "quantum cryptography" OR "quantum key" OR "quantum teleportation" OR "quantum information" OR "quantum technology" OR "quantum technologies" OR “quantum gates" OR “quantum register" OR “quantum contextuality" OR “quantum decoherence" OR “quantum communication" OR “quantum memory" OR “quantum memories" OR “quantum repeaters" OR “quantum state transfer" OR “quantum zeno dynamics" OR “qubit" OR “qutrit" OR “qudit" OR “quantum correlations" OR “quantum entanglement" OR “quantum discord" OR “quantum noise engineering" OR “quantum state engineering" OR “quantum protocols" OR “quantum annealing” OR “quantum logic gate” OR “quantum internet” OR “quantum repeater” OR “quantum memory” OR “quantum photonics” OR “quantum photonic” OR “quantum biology” OR “quantum machine learning”)

OR

TI=("quantum simulation" OR "quantum imaging" OR "quantum sensing" OR "quantum sensor" OR "quantum computation" OR "quantum computing" OR "quantum computer" OR "quantum coding" OR "quantum programming" OR "quantum error correction" OR "quantum error correcting" OR "quantum circuits" OR "quantum algorithm" OR "quantum algorithms" OR "quantum network" OR "quantum networks" OR "quantum channel" OR "quantum channels" OR "quantum cryptology" OR "quantum cryptography" OR "quantum key" OR "quantum teleportation" OR "quantum information" OR "quantum technology" OR "quantum technologies" OR “quantum gates" OR “quantum register" OR “quantum contextuality" OR “quantum decoherence" OR “quantum communication" OR “quantum memory" OR “quantum memories" OR “quantum repeaters" OR “quantum state transfer" OR “quantum zeno dynamics" OR “qubit" OR “qutrit" OR “qudit" OR “quantum correlations" OR “quantum entanglement" OR “quantum discord" OR “quantum noise engineering" OR “quantum state engineering" OR “quantum protocols" OR “quantum annealing” OR “quantum logic gate” OR “quantum internet” OR “quantum repeater” OR “quantum memory” OR “quantum photonics” OR “quantum photonic” OR “quantum biology” OR “quantum machine learning”)

Table A.1: A list of complementary data resources for QT stakeholders

Provider	Context	Stakeholders	Link
Quantum Computing Report by CGI	Limited to quantum computing	Government/Non-Profits, Private/Startup Companies, Public Companies, Universities, Venture Capital	https://quantumcomputingreport.com/players/
QURECA	Public initiatives in QT	Public Organizations, Funding Agencies	https://qureca.com/quantum-initiatives-worldwide-update-2023/
The Quantum Insider	Commercial dataset (paid access)	Private/Startup Companies, Public Companies, Venture Capital	https://app.thequantuminsider.com/
Inside Quantum Technology	Commercial dataset (paid access)	Market Reports, Historical Data	https://www.insidequantumtechnology.com/data-services/
National Quantum Initiative	Detailed reports but no curated dataset available	Academic and Industrial Stakeholders	https://www.quantum.gov/publications-and-resources/publication-library/
European Patent Office	Detailed patent analytics report with some available curated datasets	Industrial (patent holding) Stakeholders	https://www.epo.org/searching-for-patents/business/patent-insight-reports.html
Quantum Flagship	A self reported directory of QT stakeholders in Europe	QT Stakeholders in Europe	https://qt.eu/about-quantum-flagship/the-european-community/directories
(Kaur & Venegas-Gomez, 2022)	A focused study on the quantum workforce development	Education Initiatives, Conferences, Courses	https://doi.org/10.1117/1.OE.61.8.081806

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Article 3.1: Navigating the Quantum Divide(s)[151]

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This article explores the potential divides from emerging quantum technologies (QT) on society, covering impacts on science, technology, geopolitics, and societal structures. We aim to challenge the concept of a single "quantum divide" by offering a comprehensive view. We propose four divides: in science, technologies, between countries, and within societies. The "Quantum Divide in Science" highlights gaps among scientists and access inequalities in research communities. The second divide, "Quantum Divide in Technologies through Path-dependency," looks at technology adoption processes. The "Quantum Divide between Countries" examines adoption reasons and outcomes across countries with varying development levels. Lastly, the "Quantum Divide within Societies" addresses societal implications, one of the most discussed in literature. We propose directions to navigate these divides, noting their interconnectedness and impact on innovation ecosystems. This study guides those interested in the quantum divide, navigation strategies, and QT's influence on scientific, technological, international, and societal institutions.

Keywords: Geopolitics, Path-dependency, Societal impact, Quantum divide, Quantum technologies

I. Introduction

The first quantum revolution occurred in the early 20th century and has had a profound impact on our daily lives, resulting in the development of a wide selection of impactful outcomes ranging from the computer to the nuclear weaponry. The second quantum revolution, which started in the 1980s, is expected to have similar effects before mid-century [1]. As being the cause of these revolutions, quantum mechanics brought new discoveries in the understanding of fundamental principles of nature. The first quantum revolution emerged under the leadership of Erwin Schrödinger and Werner Heisenberg in the 1920s. This revolution came to life with quantum mechanics, which introduced the wave function, Heisenberg's uncertainty principle, and the intrinsically probabilistic nature of quantum events [2]. The ideas of energy quantization, wave-particle duality, and the uncertainty principle have led to advances in various fields of science and the development of many modern technologies such as lasers, MRI scanners, and transistors [3]. With the advent of the second quantum revolution, this trend is only expected to accelerate. Simply put, these developments are creating new opportunities for exploration and expanding our understanding of the physical world [1], and our ability to shape it.

In his famous book 'The Structure of Scientific Revolutions', Kuhn suggests that in a given time there is usually one paradigm that makes up the way of experiencing, understanding, and interpreting the world. This paradigm has the best answers to the questions of the scientists at that time. During periods of 'normal science', as termed by Kuhn, scientists operate within this paradigm, engaging in problem-solving based on the established theories and practices.

[151] https://ieeexplore.ieee.org/document/10914562/

However, through time, the existing paradigm fails to provide adequate answers to the new questions raised, and as a result, tension in the system that calls for a revolution starts accumulating. Eventually, the existing paradigm shifts to one that has better answers and with those answers, carries a new way of understanding and living the world. A common example of this shift is given as the transition from Newtonian to Einsteinian laws of physics, as explained by Kuhn [4]. This Kuhnian conceptualization of scientific revolutions and paradigms are reformulated in the 1980s for the field of economic development via the neo-Schumpeterian quest to understand innovation and processes (and difficulties) of technological catch-up by authors such as Dosi [5] and Perez & Soete [6]. This formulation relies heavily on the distinction between invention and innovation, and the fact that "…*the space of the technologically possible is much greater than that of the economically profitable and socially acceptable*" [7, p.186]. Thus, which technology takes the lead in certain areas compared to its alternatives and for what reasons heavily relies on factors outside of the bounds of that technology's technical capabilities. Societal and economic stakeholders from government, industry, academia, and civil society all play a role in setting the conditions for adoption and trajectory of innovation. This line of thinking is aligned with the quadruple helix model of innovation [8] popularized in late-2000s, which emphasizes the importance of integrating the perspectives of all the stakeholders, including the media-based and culture-based public, compared to the previously prevalent triple helix model [9] that locates the crux of innovation in the university—industry—government relations. Hence, a technological revolution both impacts and is impacted by a wide range of stakeholders in our society. It goes beyond just the scientists working on the fundamentals or the engineers and designers who turns creates the products, all four types of stakeholders have a role to play in bringing the new paradigm.

Every technology within the constellation of QT has its revolutionary promises. Quantum computer's ability to perform some complex calculations much faster than classical computers gives it a significant computational advantage [10]. Quantum key distribution (QKD) and quantum communications offer a new level of security and novel methods in data transmission and protection against cyber threats through unbreakable encryption [11], and the groundwork for a potentially novel new infrastructure, the quantum internet [12]. There are practical applications in fields like navigation, environmental monitoring, and medical diagnosis through the use of high-precision quantum sensors [13], which can also improve precision in areas like imaging techniques, quality control, and metrology [14]. Quantum simulation offers better understanding and control over materials benefiting from quantum properties, such as superconductors, and have the potential to revolutionize energy storage and electronics through enabling more advanced materials science research [11]. Furthermore, quantum mechanics is still driving fundamental scientific discoveries, reshaping and advancing technology and research [11].

It should be noted that despite the promises made by some scientists and entrepreneurs, the tangible products of the QT with revolutionary impacts, are not anticipated in the immediate future [15]. Consequently, the element of uncertainty in the specifics of these advancements is undeniable. It is safe to argue that most research in new QT is still emerging out of their era of basic research [3], where no dominant design is established. Quantum computers of the future can use superconducting circuits, ion-traps, photonics, neutral atoms, or another modality of physical realization, all of which have different advantages and disadvantages in terms of

operation speed, coherence times, and connectivity which will directly impact the application areas they will be able to bring most value to. They have different value chains, different expertise pools, and different material requirements, which results in varying configurations of necessary partnerships between companies and countries. Similarly, the future of the quantum internet is also in flux, where different quantum repeater models with or without memories, entanglement distribution methods, and even infrastructure types (fiber vs. satellite) are still in negotiation between the stakeholders, and no clear path forward is laid on the table that has a buy-in from all the stakeholders. However, regardless of the exact configuration and design of the tangible outputs in the mid-to-distant future, a constant reality is that with any scientific or technological breakthrough of this magnitude, divides can emerge over who will benefit and who will be harmed from the widespread introduction of these technologies to society.

In evolutionary economics, one way to study such situations is the path-dependency [16] approach, which is particularly useful in imagining the potential trajectories of emerging technologies, and their impacts on different stakeholders and various areas of life. Decisions of the past put a constraint on the range of decisions available and their cost today, and the decisions today will put a constraint on the range of available decisions and their cost in the future. This holds true both for a country and a company, where policy decisions and implementation for a country, and the managerial decisions and implementation for a company, cause certain paths to be prioritized over others and alter the cost structure in different periods of time. For example, a company heavily invested in ion-trap technology in the earlier stages of development in quantum computing will have a higher cost of integrating itself into the global value chain if the dominant design for quantum computers ends up being a different modality (like superconducting or photonics). There are many such decisions in the early stages of a radical innovation that has the potential of drastic impact on different stakeholders in the future, creating divides between them.

In the context of technology and society, the concept of “divide” generally refers to a significant gap that exists between different groups or regions with respect to ‘access to’ and ‘utilization of’ a particular technology or resource, which causes inequality. This term was popularized in literature to point out divides emerged in the case of the information age [17]. Therefore, the divide is mostly used to describe situations where some individuals or communities are able to access and benefit from certain technologies while others are unable to do so, leading to digital, technological, or information segregation. In our case, the concept of quantum divide corresponds to a possible gap between groups and/or countries in any conceivable area of life, mainly caused by the lack of interaction or understanding of quantum mechanics, technologies, and their possible outcomes [18], [19]. The importance and significance of bridging the gap between theoretical and practical applications of QT is already pointed out by several studies in the literature [18], [19], [20].

In previous studies, the notion of divide is mainly constructed from the perspectives of a divide between countries and within societies. They emphasize the need to address the challenges associated with QT and increase collaboration among stakeholders such as researchers, industry experts, and policymakers. In our work, we follow the line of thinking that more than one type of divide needs to be taken into account in order to talk about a comprehensive and inclusive development environment for QT [19]. In the existing literature, there is a definitional

gap in the categorization and evaluation of these divides. To address this gap, we propose four different types of quantum divides arising from the four major stakeholder areas defined in the quadruple helix model [8] to be described and analyzed in this work. The benefit of evaluating the phenomenon of the "divide" under four distinct headings lies in moving away from a single-focused, one-dimensional perspective, allowing for a more comprehensive examination of events and phenomena in their interconnected contexts. This paper leans towards a scenario analysis approach. By analyzing current data and proposing trends to be followed in the future, it differentiates itself from existing studies in the literature. While prior works focus on observing QT-related divides within a single domain, this paper offers a multidimensional perspective to the analysis and projection of the "divide," contributing a unique and holistic approach that sets it apart. The quadruple helix model identifies academia, industry, governments, and civil society as the relevant stakeholder groups for a functioning innovation ecosystem, we propose a corresponding divide for each of these. These are the quantum divides in science, in technology through path-dependency [16], between countries, and within societies. Therefore, while the majority of the previous studies have taken the element of access as the main source of division and focus on divides within societies and between countries, we argue that a more nuanced approach is better suited for enabling a wider range of actions from different stakeholders within innovation ecosystems. Expanding the discussion beyond the country and society-wide scopes provides an opportunity to bring in researchers, technology developers and engineers from industry and business stakeholders, especially those with managerial responsibilities, into the debate on how to navigate these divides and how to identify the conflicting interests between different stakeholders with respect to them.

II. Why Are Quantum Technologies Expected to Result in a Divide?

It is argued by Manuel Castells that we live in a network society [21]. Castells' theory of the Network Society, particularly concerning digital technologies, highlights the significant influence of informational networks, like the Internet, on modern society. This viewpoint suggests that networks created by major historical events—whether through innovations, inventions, or political actions—have a deep impact. For example, the advent of the internet and smartphones has drastically altered our communication methods and business operations, changing everyday life and social interactions. In such a society, the key social structures and activities are organized around electronically processed information networks. Within this context, the digital divide is argued to be not limited to the simple matter of having access to technology, the internet. It is a complex phenomenon that involves a range of factors beyond just physical availability. This line of thinking contrasts with some others. For example, Michael K. Powell, the Federal Communications Commission chairman of the time, refers to the digital divide in 2001 as calling it a "Mercedes divide". From his point of view, it is a similar case to "*wanting a Mercedes car, but not being able to have it*" [22]. In comparison, Castells argues [23] that a divide caused by technological developments has far-reaching implications for knowledge creation and destruction, as well as power dynamics. It is "a complex interaction" in a social structure that holds the sources of inequality and social exclusion (p.781). It is not as simple as wanting but not having a Mercedes car.

These divisions often arise due to the strategic actions and managerial decisions of various stakeholders with external motivations, not aiming at creating a divide. Such motivations include pursuing economic development, attaining self-sufficiency, or gaining political power in the case of countries. For example, the World Bank highlights the importance of self-sufficiency and suggests that policymakers should support the development of local data infrastructures [24]. However, it is observed and discussed in the literature [25] that for smaller countries without significant market size, such regulations can cause main providers to not invest in local infrastructure. This, in return, limits access to these services and increases costs for local businesses, preventing entrepreneurs of these countries from fully participating in the digital economy and further exacerbating the digital divide.

QT are also expected to be transformative technologies by many [15, 26, 27], for having the potential to significantly impact and disrupt various sectors, including healthcare, defense, finance, energy, and others. In these lines, the concept of quantum divide is sometimes constructed as "*challenges, between regions, between nations, and between rich and poor within nations, around creating more equitable access to quantum computing*" [19, p.3]. Furthermore, in this context accessibility is identified as a core value in the field of QT [20, p. 274], [28] and unequal access is perceived as the main cause of the quantum divide [29]. On the other hand, some conceptualizations of the quantum divide refer to it as a “knowledge gap” [18, p.242], and put the distinction between individuals engaged in QT development and those who are not [30], or even the knowledge gap between quantum scientists and society [31]. In short, the quantum divide, similar to the concept of digital divide, is conceptualized in the literature primarily associated with having access to devices and knowledge on QT or not.

It should be noted that QT are not the only set of technologies that is expected to result in a divide, divides emanating from other emerging technologies such as artificial intelligence (AI), robotics, and nanotechnology are also expected and discussed in the literature. There are recent studies [32] and reports published on the “AI Divide”, such as a recent one from the United Nations and International Labour Organization, and on the “Robotics Divide” [33, 34]. Similar discussions can also be found on nanotechnology dubbed as “Nano-Divide” [35, 36] dating back to 2006. Some might argue that since we do not see a nano-divide on the level of a digital divide today, the same can be expected for QT. However, it is important to be prepared for the case if such extreme disparities arise, especially since globally more than $55 billion of mostly public investments are designated for QT [37] development. Given the revolutionary nature of QT [1], the high levels of investment globally, and a strong strategic interest from important actors from NATO [38] to the European Commission [39], it is only expected that QT might result in a divide which has far-reaching implications for knowledge creation and destruction, as well as power dynamics, impacting all stakeholders [23].

A. Types of Divides

As in all emerging technologies supported by public funding, the main preferred result of those impacts can be thought to be increasing welfare in general. As has been mentioned in the previous section, there are various sectors that are expected to be affected by QT that can serve that direction. Furthermore, one of the far-reaching impacts of the QT, besides the impacts on “*(leader) countries’ industrial bases and providing economic and national security benefits*,” has

been argued as creating jobs [29]. Beyond sectoral influences, QT can play a role in reshaping social and cultural landscapes. This prediction, while seemingly speculative, underscores the profound entanglement of technology with the fabric of society, influencing political, social, and cultural spheres far beyond a mere tool. QT embodies the values and aspirations of the communities that forge and adopt it. These effects, undoubtedly, will not manifest in the near future, but they can work their way through means such as humanities [40, 41], games [42, 43], music [44], and arts [45].

Considering that QT has been noted as having strategic importance for governments [38, 39], has disruptive potential for many of the critical sectors [29], can scientifically play a revolutionary role [1], and is already impacting the social and cultural spaces [44], we formulate the different types of divides that could potentially arise by covering the entire stakeholder base of the quadruple helix. We propose four types of divides that have the potential to emerge during the development, adoption, and usage processes of QT. These are the quantum divide in science, the quantum divide in technologies through path-dependency [16], the quantum divide between countries, and the quantum divide within societies. In the following subsections from A.I to A.IV we introduce and describe these types of divides. The discussions on how to navigate them are reserved for Section III.

A.I. Quantum Divide in Science

There are no specific references to the term 'scientific divide' in the existing literature. Nevertheless, we find this term suitable to characterize what we have in mind. The concept of a scientific divide can be built upon the concept of paradigm by Kuhn [4]. In a Kuhnian sense, the raising of questions to which the existing paradigm fails to provide adequate answers to is closely linked with the ability of existing scientists, which is ironically built from within the previous paradigm. This ability, although mostly attributed to the conceptual infrastructure, is also closely linked with the physical infrastructure of science, i.e., the instruments and tools that a scientist can access. The true outcomes of the Copernican revolution in astronomy were only realized after the construction of Uranienborg, the first custom-built observatory in modern Europe, and later the invention of the telescope. This enabled not only providing better and alternative answers, but also expanded the opportunity space of questions that can be asked by that era’s scientists and philosophers.

With this description of the scientific paradigm in mind, let us construct the concept of the scientific divide in QT with two branches. First is the new scientific tools and techniques emanating from QT. We can expect that an emerging set of QT that relies on quantum information science (QIS) can result in similarly revolutionary impacts of those that were previously developed relying solely on quantum mechanics [1]. The role of quantum mechanics in understanding the behavior of physical objects have already influenced the priorities and research focus in key research areas such as materials science, with an increasing emphasis on designing materials with specific quantum properties for technological applications. A further shift in capabilities among certain scientific areas can be caused by the introduction of new scientific tools and techniques. Common techniques, such as scanning-tunnelling microscopy [46] and various spectroscopic methods that rely on quantum principles already lead to a shift in how experiments are designed and interpreted in many fields of physics and materials science.

Furthermore, the utilization of techniques coming from QT already played a role in the redefinition of the kg (SI unit for mass) in 2018 [47] and kickstarting the recent surge in gravitational wave astronomy [48] which resulted in the observation of gravitational waves from two black holes merging and the following awarding of the Nobel Prize in Physics 2017 for LIGO.

The tools enabled by QT have applications beyond physics and chemistry as well. An example is the recent progress in developing magnetoencephalography with optically pumped magnetometers (OPM-MEG) [49] which is a promising tool for the next generation of functional neuroimaging [49]. MEG is a functional neuroimaging technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain, using very sensitive magnetometers. Current MEG devices require considerable physical infrastructure like cryogenics and superconducting devices, they are similar to MRI devices in their physical configuration. In comparison, the novel OPM-MEG devices are at the size of a bike helmet, a helmet specially 3-D printed for the subject's head with dozens of synchronized quantum sensors placed on it. Enabling the utilization of portable and wearable quantum sensors that can perform MEG operation enhances the opportunity space for questions that can be asked by neuroscientists using these tools for data gathering from subjects in motion. There are already reports dating back to 2018 [50] of OPM-MEG devices being used for research on people playing table tennis, drinking coffee, and performing other physical activities, which were previously not possible due to the limitations of the experimental tools. These techniques can quickly be adopted by teams of scientists using MEG devices for their research, as they already possess the capabilities to work with data generated from these devices. However, according to a market analysis report in 2022 [51] there are only around 200 MEG scanners in use worldwide for both medical and research purposes, which limits the scientific expertise that has any hands-on experience in MEG-based neuroscience to research groups in a handful of countries. These experienced teams will most likely be the first customers of companies producing OPM-MEG devices, have the first access to their capabilities, and be the ones to kickstart a surge of activity in their fields.

The second branch is the adoption of new tools and techniques by different scientific communities resulting in a gap between them in their ability to ask or answer questions arising on the peripheries of normal science. These divisions can be related to funding, representation, educational access, or variations in scientific achievements, among others. Consider the OPM-MEG case. Eventually, the devices will be adopted by others and overall, empower their relevant scientific communities in more countries than currently using MEG techniques today, but this can take varying amounts of time depending on the trajectory of the technology. Therefore, it initially contributes heavily to the creation of a divide in scientific capabilities within certain research communities with respect to their ability to conduct research using these newly emerging quantum tools.

It can be argued that the historical emergence of quantum mechanics made a variety of interdisciplinary collaborations -between scientific fields that were traditionally separate- possible. The roots of the periodic table go back to the mid-19th century, however unlocking the true potential of the periodic table had to wait until the formulation of the Pauli exclusion principle in 1925. Similarly, Schrödinger's ideas on applying quantum principles to understanding the

biological concept of life contributed to the discovery of DNA [52]. As has been seen again and again, progress in scientific research is more fruitful in the case of collaboration.

In the case of QT, quantum physics and computer science coming together enabled research into quantum computing, making physicists, engineers, and computer scientists work more closely to build actual quantum computers. Today, the field of QIS, which includes quantum computing, cryptography, and communication, is becoming a distinct field with its own focus and experts [53] and its own discipline-culture [54, 55]. QIS focuses on using quantum properties for processing information and can be considered as the scientific basis for a considerable portion of the QT associated with the second quantum revolution. However, certain approaches and formulations beyond the immediate applications of QIS in physics and computer sciences are not reaching or being accepted by their intended scientific communities. For instance, it is argued in the literature [56] that quantum biology is not being regarded as a "legitimate" scientific field, although it carries significant potential in many areas of biology and life sciences. The reasons for this are identified as the absence of a cohesive quantum biology community, lack of experimental verification, and the continued presence of scientific silos at institutions [56, p.2]. Similar arguments can be applied to the lack of adoption of quantum chemistry techniques using quantum computers for full model simulations by chemists who are sticking with widely available density-functional theory (DFT) modelling, even though quantum computers hold great potential for the field [57]. Another example in the literature is about the potential impacts of quantum computers on research in humanities from data preparation, techniques and methods like clustering, and classification to various approaches for data analysis [40], [41]. Likewise, some authors argue [58] how basic principles of quantum mechanics can be applied to decision-making paradoxes in psychology and used for modelling information in finance and economics. Even between the fields of QT, there are versatile opportunities for further collaboration and development that are not being fully explored, such as examining quantum metrology through the lens of QIS [59].

There are, of course, some who take the risk of exploring these potential new opportunities. For example, according to The Guy Foundation [60], there are almost 50 quantum biology research centers distributed to more than 10 countries, and there are particular examples of strong commitment such as Cleveland Clinic in Ohio signing a 10-year partnership with IBM focusing on advancing the pace of biomedical research through the use of quantum computing [61]. Some of these research efforts will inevitably lead to dead ends. However, it is only expected that successful endeavors will end up providing their research groups with first mover advantage and the opportunity of pioneering previously unexplored topics.

As the scientific divide in the QT context is a nuanced conceptualization, we want to provide two analogical examples related to scientific fields from the era of not the second quantum but the digital revolution, particle physics and library sciences. The ties between particle physics and digital technologies go back quite a while, as it was a field requiring high computational capabilities. For example, some of the most important protocols that enable the World Wide Web (WWW) were first developed by Tim Berners-Lee in 1989 while he was a fellow of CERN, as CERN was the largest internet node in Europe back then. This early adoption of digital technologies, when combined with the resources provided by CERN, enabled particle physics to grow as a truly international scientific endeavor. As an outcome of this, the 2015 article on the

first measurement of the newly discovered Higgs boson had 5,154 individual contributors [62], breaking the record for having the largest number of contributors to a single research article. Another example is the field of library sciences and the integration of bibliometrics with the developing digital infrastructure in mid-1990s [63], which also contributed to the development of digital tools, such as Google search. In both cases, tangentially relevant fields which fundamentally have nothing to do with the development of the physical technologies and the infrastructure of the digital revolution, benefitted tremendously and co-produced some of the core functionalities of the digital infrastructure we all use today, such as the internet.

TABLE I: Available/Adopted Scenarios

Available	**Adopted**
Has access	Uses
Has access	Does not use
No access	Would use it if had access
No access	Would not use it even if had access

In summary, the two branches of the quantum divide in science we highlight in this section are primarily the availability and adoption of new scientific tools and techniques emanating from QT in general and QIS in particular. The branches can further be diversified, but the main formulation of a gap between those who have potential access to the tools and knowledge and those who do not remain. The second branch adds a further dimension, a gap between those who can realize this potential via early adoption, hence having an impact on the trajectory of that technology, and those who will not. A summary of these four scenarios can be found in Table I. Therefore, the real sizeable gap will expectedly be between two groups: (i) those with potential access to the tools and knowledge, who will adopt these successfully to answer questions on the periphery of normal science, and (ii) those without the potential access to the tools and knowledge who would not realize this potential even if they had the opportunity, hence missing to identify the point in time where these resources will finally become potentially available for them.

A. II. Quantum Divide in Technologies through Path-dependency

In all emerging technologies, governments, firms, scientists, and societies play a role in the development of that technology in the quadruple helix framework of innovation ecosystems [8]. From this point of view, it is natural to expect that the interactions between government, industry, academia, and civil society stakeholders impacts the trajectory of an emerging technology. As introduced in Section I, the Kuhnian conceptualization of scientific revolutions and paradigms

are reformulated for the field of economic development in the name of the neo-Schumpeterian effort to understand innovation and processes (and difficulties) of technological catch-up in the 1980s by authors such as Dosi [5] and Perez & Soete [6]. This formulation relies heavily on the distinction between invention and innovation, and the fact that "…*the space of the technologically possible is much greater than that of the economically profitable and socially acceptable*" [7, p.186]. Thus, which technology takes the lead in certain areas and for what reasons heavily relies on factors outside of the bounds of that technology's technical capabilities. Societal and economic stakeholders from government, industry, academia, and civil society all play a role in setting the conditions for adoption and trajectory of innovation.

In the context of QT, we make use of another notion from evolutionary economics, path dependence, into this discussion to formulate our theoretical ground. The concept of technological path dependence suggests that the managerial choices made early in the development of a technology can have a lasting impact on the direction and trajectory of research and development in that field [64, 16]. Antonelli defines path dependence as "...*the set of dynamic processes where small events have long-lasting consequences that economic action at each moment can modify yet only to a limited extent*" [64] (p.1). The concept can be operationalized in a way to explain both internal impact and external impact (see Figure 1).

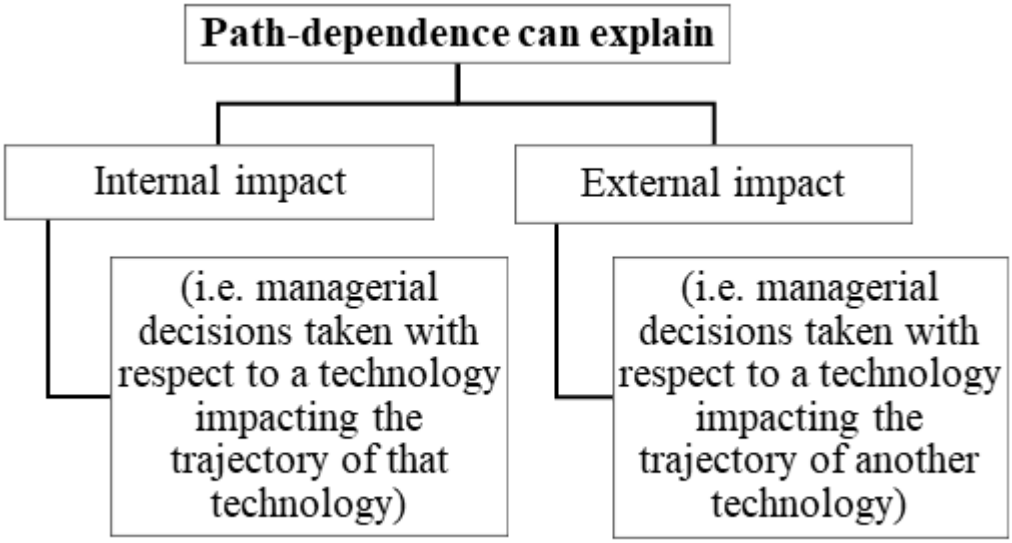


Fig. 1. Impacts of path-dependence.

Therefore, we can state that any adoption of a developing or ready-to-use technology by governments, firms, universities or societal stakeholders result in an environment that prioritizes some potential paths while blocking or deprioritizing others and making some other technology's development or adoption easier or harder in the future.

The selection of specific QT by different stakeholders can lead to a diverse global technological landscape, with different countries specializing in various areas [65, 66]. Being able to come up with the dominant design can lead to increased economic competitiveness, technological

leadership in QT, unique security capabilities for a while and exerting international influence. Some nations/firms may excel in rapidly developing a first working version of fault-tolerant large scale quantum computers, achieving the first-mover advantage. This can cause the infrastructure to “lock-in” to that certain modality, regardless of the inefficiency of the technology compared to the other possibly more efficient, yet not realized designs. This hypothetical, but well-known process assures the cruciality of the timing [67]. A partially dominant design that leads to at least some favorable returns on investment (ROI) might attract more investment, leading to further improvements, leading to higher ROI attracting more investment and so on. This is referred to as the virtuous cycle [68]. The first to achieve a functioning virtuous cycle can ride the wave of early-stage high growth period of any radical technological innovation. This results in a high switching cost for the later adopters due to most of their previous investment becoming sunken cost depending on when they decide to switch from their modalities to the modality of the dominant design, eventually causing a lock-in where it practically becomes impossible for any other modality to compete with the dominant one [67].

The concept of virtuous cycle for QT is proposed in the literature [68] with respect to how the semiconductor industry aligned itself related to transistors. In this cycle, the adoption of new technology in products leads the industry to make more money, which is then reinvested in the development of newer technology. This is identified [68] as the main driver of Moore’s law, the push for making the number of transistors in an integrated circuit double every two years. It is argued that this virtuous cycle of development in transistors also effectively ruled out alternative technologies for computation via locking-in the information technologies industry to work with silicon transistors for the last 60 years [68] (p.18). Before the invention of the transistor, if you asked a researcher to envision the future of computation, the most probable reply that you get would be miniature vacuum tubes. A similar shift in the dominant modality of physical realization of quantum computing is also possible. Currently, companies like IBM, Google, Rigetti, IQM, and others are focusing on developing superconducting circuits-based qubit systems. However, there are others such as IonQ, Quantinuum, and Universal Quantum working on trapped ion quantum computers, and those such as Xanadu and PsiQuantum working on photonics-based quantum computation. It is entirely possible to look back at the current superconducting circuits-based devices available on the cloud today and consider them as archaic modes of doing quantum computation, as we do for vacuum tubes of the 40s.

In order to evaluate the developmental trajectory [5] of QT, the national initiatives related to QT in various countries and their collaborative efforts on an international scale carry significance. This is because that they don’t only have a direct impact on the quantum divide between countries, but also the policies and funding decisions of governments significantly impact the direction and rate of development in QT. Countries allocate resources and establish policies that encourage research, development, and commercialization in specific QT domains or even on specific modalities for quantum computers, networks, and sensors. Countries generally choose the technologies to fund according to their existing capabilities within their national infrastructures. Moreover, international collaborations as well, are driven by both innovation and risk-averse strategies [69]. By intending to work with countries that have similar approaches, nations aim to minimize the chances of facing unexpected challenges along the development path they are on. Hence, it is only expected that the way countries decide on their pioneer QT,

choose which technologies and modalities to support, and collaborate internationally are interconnected.

On a similar line, countries that align on not just dominant design but also values expectedly gravitate towards each other. This is put forward in the literature [70] via the feature of "like-mindedness" in the partnership of the AUKUS security agreement between Australia, the United Kingdom, and the United States, suggesting that having a shared mindset is an advantage of becoming pioneers in the quantum field. This collaborative strategy focuses on strengthening each other's existing systems, instead of exploring completely different paths. Furthermore, the National Quantum Coordination Office of the United States [71] presents international partnerships formed based on the concepts of "shared values/commitments", "common dedication/priorities", and "history of scientific engagement" in such scientific and technological advancements between countries. Under the requirements of international collaborations, whichever technology can be supported the best in terms of material and human capital is likely to be a winner in this pragmatic decision-making process. In other words, shared perspectives, such as a common understanding of determination and values within a governance domain, result in a strategic partnership to work on specific technologies or designs that will support the aimed value and make nations stronger together. Consequently, it is plausible to assert that the values of the nations, which are strong and/or compatible enough to form an alliance, evolutionarily affect the path-dependent process of technology development and adoption.

Combining these, we can expect a quantum divide in technologies to emerge at the point of lock-in [67], not only between countries, but the techno-economic paradigm options beginning to form around different dominant modalities [7], especially for quantum computers and networks. Innovation ecosystem actors of all types in the quadruple helix model [8], academia, industry, government, and civil society, may find themselves on different ends of the spectrum in terms of their involvement with the final dominant modality and system designs. There is a multitude of operational options and room for managerial discretion in the future technological state of QT. Different modalities of implementation for QT can be thought of as technologies where “the adoption of both increases profits by less than the sum of the profit gains from the adoption of both alone” in the path-dependency frame [16, p.7]. This indicates that there will be a market pull towards a tipping point after which lock-in is settled and in a relatively short period of time any previous investment into competing modalities becomes mostly sunken cost. If this adoption is also in alignment with the formation of a new and stronger virtuous cycle, then any new investment into competing modalities also becomes mostly in vain. Leading to an outcome where actors within the helix that invested their time, effort, resources, and attention into anything other than the locked-in modality find themselves in a challenging position. Their situation would resemble having huge investments in vacuum tube manufacturing capabilities in the mid-50s or a movie-renting establishment serving CDs in the age of high-bandwidth streaming services on mobile devices.

A.III. Quantum Divide between Countries

There are several aspects that we can consider as the factors causing the emergence of a quantum divide between countries. However, in the context of this article and what is covered in

earlier sections, we will limit our analysis to two possible causes for this divide which are summarized in Figure 2.

As discussed in the literature [72], numerous investigations in the realm of international strategy indicate that each nation establishes its unique knowledge networks, institutional settings, and economic structures, all of which can consistently impact innovation endeavors within domestic markets, no two countries are the same. In determining a nation's technological trajectory, these settings, networks, and structures serve as a starting point and directly affect the country's technological capabilities and options. Nations have various criteria to consider when adopting or developing a technology. These criteria are logically based on both the features of the technology in question, like trade costs and productivity levels, and/or the country's ideology, strategy, and capabilities. Although we suggested that whether there is access to technology or resources is not the only determinant of the divide, it is an undeniable aspect of it. It is included in the capability aspect and carries a historical burden for being a cumulative incident, related intrinsically to the path-dependency [16] introduced earlier. To give an example from the digital divide, a crucial aspect of this divide is the availability of adequate international bandwidth, which is essential for smooth and unrestricted access to the global internet [17]. It is also suggested that lower-income countries often struggle with collecting and effectively utilizing data due to insufficient infrastructure and expertise. This results in a situation where previous decisions, such as lack of investment into infrastructure, a botched attempt at digital sovereignty via overregulation, or educational priorities resulting in an inadequate pool of expertise limiting the options of a country for digital transformation to gap the divide.

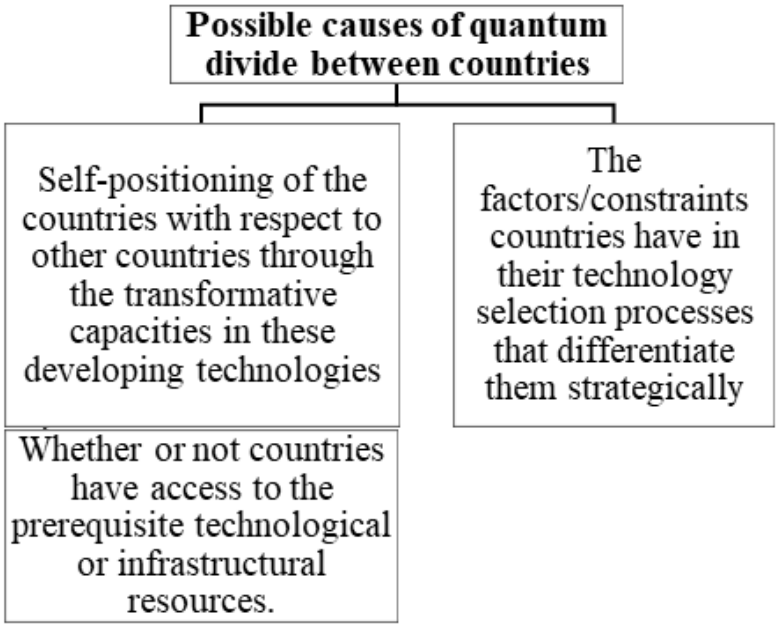


Fig. 2. Causes of quantum divide between countries.

As discussed above, the development of new infrastructure is inherently linked to and built upon the foundations of the previous infrastructure. An example from the QT field is that the

quantum internet [12] requires a well-functioning ‘classical’ internet to operate. It will be built upon the existing infrastructure and not replace it. The challenge for QT in this case arises when a seemingly innocent motivation for “self-sufficiency” is pursued without understanding how technology and infrastructure developments are interconnected. Self-sufficiency in strategic areas is usually referred to as a desirable target for many countries [73], and a general definition of self-sufficiency is given [74] as "*a situation in which a country or region's domestic production equals its domestic effective demand*" (p.13). This perspective is adopted by a growing number of nations to emerging technologies to varying degrees because these technologies have a strategic role. It is framed [73] as “technological self-reliance” and is being put forward as an explicit goal by certain countries. For example, China states that it aims for technological self-reliance in its most recent five-year plan [75].

In the context of QT, this aspect is briefly covered in the literature as protectionist impulses [26], especially with a focus on UK’s National Security & Investment Act, the multi-state Wassenaar arrangement, and the US’s ITAR regulations, which are utilized to support outcomes such as the UK-US Joint Statement on co-operation in QIST (Quantum Information Science and Technology). These can be extended to cover the AUKUS security agreement between Australia, the UK, and the US, and the Commission Recommendation on critical technology areas for the EU's economic security for further risk assessment with Member States [76], which includes QT as one of the recommendations that is already accepted by the EC. Some authors even argue that pursuing these protectionist impulses too strongly might lead to moral isolationism for Europe [77], and is being fueled by an increasing adoption of techno-nationalism [78], an argument on linking a nation's technological capabilities and self-sufficiency to its state security, economic prosperity, and social stability.

These are examples primarily emanating from defense and security concerns. However, a more general shift in the language in recent years is hard to miss in the QT domain. The Quantum Manifesto [79], published in 2016, calls for encouraging international collaboration through new international funding mechanisms in science and promotes international collaboration, exchange, and networking of people and information between different centers in innovation. In contrast, the sub-section dedicated to international collaboration in the preliminary Strategic Research and Industry Agenda (SRIA) document of the Quantum Flagship published in 2022 [80] and laying out recommendations for the roadmap to 2030 is titled “International Collaboration / Export Control Regulation” and international (extra-European) partnerships are recommended in the entire SRIA only within the framework of standardization efforts. Even within the EU, the discussions on going wide or going tall, meaning either distributing the investment and infrastructure to all the member states versus keeping them focused in certain areas/countries for increased efficiency and economies of scale, is an active topic of discussion. Central member states that can support major national initiatives on QT (such as Germany, the Netherlands, and France) are arguing for European support towards their home efforts meanwhile member states with lower levels of infrastructure are calling for support to promote their efforts in catching up.

Naturally, the strategy discussed earlier, which focuses on enhancing current strengths through the selective development of technology, also relates to the issue of the quantum divide among countries. These strengths display themselves in scientific, political, and economic arenas may

contribute to a gap among nations based on their advancements in QT. Some in the literature [72] suggests the possibility of an argument that scientists and engineers from technologically advanced countries are more likely to concentrate on studying established technologies rather than exploring completely new directions. This may be due to a variety of factors, including the need to maintain existing infrastructure, the presence of established industry players with significant investments in existing technologies, and the pressure to deliver results. Consequently, in technologically advanced countries, the companies benefit from the positive network effects of well-established technologies, like incubation facilities or infrastructure such as clean rooms, which makes them choose the technology to develop that is supported by the already existing structure, networks, and settings. Essentially, some countries might end up getting better at certain QT, creating a gap between those who are already strong in these areas with their well-established capabilities and those who are comparatively less equipped. Surely, differing perspectives exist on this matter. For example, some argue [81, para. 4] that the development of QT is still in its early stages, "*where it is possible for small players to make a significant impact*". According to this point of view, contrary to the countries with well-established capabilities, “small players” need to identify a specific area of focus that includes originality and high risk within an emerging technology that has the potential to create a worldwide influence. Therefore, it is suggested that [81] small countries not become consumers but creators by taking the risks that bigger countries did not take.

Another topic potentially relevant for QT is the workforce size not meeting the need for labor, which is presented as a bottleneck to quantum development in the literature [82]. In the media, it is portrayed as a national security vulnerability [83] and a battle to train quantum coders [84], and many initiatives around the globe are being implemented to remedy it, with dozens of specialized QIST and QT graduate programs being formed [82, 85]. This is not very surprising considering the number of QT start-ups growing from being less than 20 in 2012 to over 400 in 2022 [86]. This, combined with the point on global mobility above, is a concern for certain countries. To be clear, being an expat or migrant researcher still has many difficulties and hurdles even in the field of QT where fast-tracking visas are being discussed, some of them beautifully described in the paper “Quantum researcher mobility: the wonderful wizard of Oz who paid for Dorothy's visa fees” [87]. However, topics such as depletion of academic reserves and senior brain drain are openly discussed in public forums and sometimes are even causing friction on panels with representatives from the US and the EU having differing opinions on it. Different regions and countries have different priorities in terms of technologies they focus on, modalities they aim to scale up, and levels of risk they wish to accommodate for potential future gain, but they all need a certain amount and type of labor for their efforts. Currently, this labor consists primarily of highly educated technical workers, mostly with PhDs in Physics or certain specialized Engineering degrees, and there are only a limited number of those.

The different priorities highlighted above can come in several shapes and forms and are, of course, subject to change with time. For example, the most up-to-date and detailed report of its time published in 2019 by the National Academies Press on quantum computing [68] focuses on two dominant modalities for quantum computers in Chapter 5, trapped ion and superconducting qubits. It considers photonic quantum computers, neutral atom-based devices, and semiconductor qubits under “Other Technologies.” In comparison, as of December 2023, the most well-funded quantum computing start-up (not associated with any major existing tech

giant) is PsiQuantum, which is working on photonic quantum computers, while the record on the highest number of logical qubits demonstrated is held by a neutral atom company called QuEra [88], both are from the US where the report was written. This type of uncertainty and rapid changes bring forth additional difficulties in planning forward. The QT landscape has a diversity of modalities being explored simultaneously. For example, in the quantum computing ecosystem, the Austrian start-up Alpine Quantum Technologies (AQT) focuses on trapped-ion quantum devices, the Finnish start-up IQM Quantum Computers specializes in superconducting, the French start-up PASQAL on neutral atoms, and another French start-up Quandela on photonic quantum computers. All these require distinct supply chains and non-transferrable skillsets up to a point, further exacerbating the problem with predicting where workforce bottlenecks may arise, creating additional layers of complexities on the skills shortage front.

We mentioned two causes that may give rise to a quantum divide between countries. The first is how countries position themselves, which we argue is highly impacted by the increasing desire and pursuit of national or regional self-sufficiency and the type of infrastructure they already have access to. Secondly, the factors/constraints they have in their technology selection processes that differentiate them strategically, which are their size, development level, existing path-dependencies, and particularly, the available workforce. A combination of these causes can lead to a considerable divide even within the class of developed economies, where successes in certain regions and countries attract more of the limited workforce there, depleting the academic reserves of other regions, hence further slowing down development in those.

A. IV. Quantum Divide within Societies

The final divide we want to explore, which is one of the most highlighted in the literature, is the potential quantum divide to occur within societies. In this section, we primarily want to focus on why this divide is the most expected one and how, in practice, QT can cause the perpetuation of the digital divide into the quantum era.

Technological changes inevitably bring social transformations. They are intricately intertwined, influencing, transforming, and constructing each other in a continuous way. The integration of new technological applications and systems necessarily alters the dynamics of how individuals communicate, work, and live. In turn, societal needs and preferences drive the evolution of technological advancements, creating a cycle in which they feed each other. Following the Schumpeterian claim of innovation causing “creative destruction” [89], one can expect QT to have a profound impact on society.

The meaning attached to technology varies, shaped by common understanding and its usage, creating a diverse foundation for social capital to thrive. Castells' Network Society theory, especially in the realm of digital information and communication technologies [21], emphasizes the transformative role of information networks, particularly the Internet, in contemporary society. It can be inferred from this perspective that the networks that have arisen as a result of significant historical developments - whether from innovations, inventions, or political decisions - have a profound impact. For instance, the emergence of the internet and smartphones has profoundly changed how we communicate and conduct business, altering our daily routines and social interactions. As an outcome of this, we can argue that there emerged an internet culture that is not defined by national borders, but by the commonalities among people regardless of

their nations. This cultural shift, driven by technological developments, highlights the potential for QT to contribute to a new cultural order, similar to the transformative impact seen with the internet.

As discussed previously, particular QT, such as quantum computers and the quantum internet [12] will not replace their predecessors, usually referred to as classical computers and the classical internet within the QT community. On the contrary, to operate functionally, quantum computers require considerable computational resources from their classical counterparts. Similarly, for quantum networks to even be able to perform certain operations (such as quantum teleportation), classical communication channels are required. Hence a quantum internet will necessarily require a classical internet to operate on. These facts already hint that the existing digital divide in societies is most likely to be directly translated into the quantum age, only becoming even deeper as not all the ones on the privileged end of the digital divide will get the quantum 'upgrade' to their infrastructure. This upgrade, first, necessitates a physical upgrade, having access to quantum computers or being able to connect to a quantum network from your region. However, as we know from the digital divide literature, having access is only a part of the game [31]. Those with the potential to develop algorithms and applications that can run on these new tools with novel capabilities will require re-training and obtaining new skills. Those who wish to consume or utilize these algorithms or applications will require a certain amount of quantum literacy [90]. The divide will widen between those who have access to these and exploit them in a timely manner and those who do not even have access to the underlying prerequisite infrastructure in the first place.

In a network society, individuals with limited access to digital resources are at a considerable disadvantage compared to those who do in terms of accumulating social capital. A relatively comedic but revealing example of this is social media. Those with access to high bandwidth connection and quality technical equipment have a much higher chance of becoming 'influencers' compared to those who do not. Access to better digital tools enables them to accumulate social capital much more effectively, literally being able to influence those on the other side of the digital divide.

A good example of how access to knowledge and skills related to QT are mediated within societies is which universities have courses or programs in QIS, hence which populations are served. As mentioned in the previous section, there are dozens of new graduate programs that are being created globally in QT [82]. A recent study analyzing the distribution of QIS coursework across 456 institutions of higher learning as of fall 2022 in the US [91] identifies that they are "inequitably distributed, disproportionately benefiting students at private research-focused institutions" and "are largely failing to reach low-income and rural students." This is not a surprising finding, but one that is indicative of the role that QT will probably play when finally, the products of it are introduced to society (such as quantum computers, networks, and sensors). They will primarily be a source for deepening the existing digital divide and will probably create a new one.

III. Navigating the Divides

Closing the quantum divides is a challenging task, even unrealistic to imagine, particularly given the existing geopolitical landscape that lacks a focus on equitable development for QT.

According to de Wolf [20], "...*governments themselves could also have an interest in monopolizing access to quantum computers*" (p.274), which will also affect access to knowledge. He emphasizes the importance of preventing "*more unequal distribution of power and wealth between America and the rest of the world, and between a few big companies and the rest of society*" (p.275). Therefore, although "closing" the gaps is challenging with governments' strategic interests, there is a bottom-up effort, and an ongoing journey to "bridge" the quantum divides.

The concept of navigating divides, as opposed to completely overcoming them, is central to this study's approach. Rather than attempting to entirely eliminate these divides, which may be unrealistic given the structural and systemic factors at play, navigation focuses on managing their impact and creating pathways to minimize their adverse effects. In some cases, navigation involves reducing the width of a divide, as seen in efforts to improve access to quantum research tools or foster international collaboration. In other instances, it requires acknowledging the existence of a divide and implementing measures to mitigate its negative consequences, such as ensuring that marginalized groups are not excluded from the benefits of technological advancements. These approaches are not mutually exclusive but are instead part of a broader strategy that adapts to the unique challenges presented by each type of divide.

Efforts for Responsible Research and Innovation (RRI) aims for accessible, affordable, equitable, inclusive, and understandable technology development and policymaking by "...*opening up conversation between science and wider society...*" [19, p.2]. There are many proposals in the literature on responsible quantum computing and responsible QT, aiming to find ways to bridge the quantum divides [19, 30, 92, 93, 94]. Furthermore, there are suggestions that democratizing access to quantum computing might help fight back against the digital divide as well [27]. Other suggestions in the literature for closing the gaps are interdisciplinary industry and academia collaborations, the role of quantum education, preparing the workforce, public understanding of QT, addressing ethical and security concerns, and having more reflexivity and responsiveness regarding the narratives and actions adopted by the actors in the QT field [95], [96], [97], [27].

In this article, we argue that it is more practical to focus on the navigation of these divides as the initial step because it allows us to include and be aware of the positions of different stakeholders in the field, some of which are, in fact, working towards creating or widening the divides. It is commendable and necessary to think about and act on how to prevent these divides from emerging and aim to bridge them if they do. However, we must also accept the fact that at least some of these divides will emerge in one form or another even if all the actors in the ecosystem wished them not to emerge, and even this is not the case. It is easy to observe that, in nationalist narratives, protectionist impulses extend beyond merely preventing the other party (depending on the perspective of the nation in question); they emphasize the necessity to 'win' the quantum race [98]. This is most clearly encountered in the language of national security and defense, where a strategic advantage, a novel capability that the 'adversary' does not possess, is something particularly sought after. Therefore, we argue that it is worthwhile and necessary to consider exploring scenarios and potential actions that can help the stakeholders of the quadruple helix to navigate these divides, especially those who have managerial duties and whose decisions will have an impact (both internally and externally, see Figure 1) on the

innovation processes, as it is more likely than not for them to become a part of our future discussions on democratization of QT [27].

A. Navigating the Quantum Divide in Science

In subsection II.A.I, we explored two potential causes for such a scientific divide to emerge. First, we considered the potential for tools emerging from QT to possess revolutionary qualities that could alter how researchers in disciplines beyond quantum mechanics and QIS conduct their work. Second, we examined the attitudes of different research communities towards the adoption of these new tools and techniques. This dynamic has already been playing out in the field of AI, where it took off following the point where AI was useful as a tool for research communities beyond just those doing AI research. An example of this can be seen in Figure 3. As of 24th August 2024, there are 3321 indexed publications in Web of Science (WoS) with the topic of “artificial intelligence” and category of “Oncology,” if we limit the search to only cover the publications before 2015, the resulting number is 68. This corresponds to an almost 50-fold increase in the number of “oncology” papers in the last decade that has the topic of “artificial intelligence.” This does not mean that AI research slowed down; on the contrary, it benefited from this adoption tremendously. There were 13,023 WoS indexed publications with “artificial intelligence” amongst their topics in 2014, as of today there are 118,927, an almost 10-fold increase in ten years.

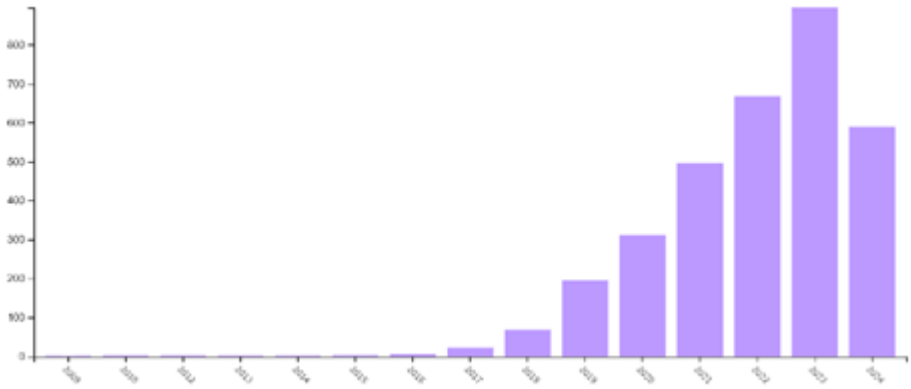


Fig. 3. Number of academic publications per year indexed in Web of Science with the topic of “artificial intelligence” and category of “Oncology” as of August 2024

A similar dynamic is expected in the field of QT when quantum computers transition from research tools to practical applications, and quantum networks are established for purposes beyond testbeds and as research infrastructure, serving as either private or public infrastructure, and when quantum sensors are deployed beyond the purpose of testing those sensors. If the promises of QT and the roadmaps of companies like IBM and public initiatives like the National Quantum Initiative Act (NQIA) and the Quantum Flagship are to be successfully realized, we may reach this point by early 2030s in quantum computers, a bit sooner for quantum sensors, and a bit later for quantum networks.

The two ways we propose to navigate this divide in science are relatively complementary, building upon the two causes we argued might result in the emergence of this divide. First,

prioritizing the adoption of these novel capabilities by relevant research communities, followed by public and shared research infrastructures with an active effort to introduce them to these communities. The second way is to bring different research communities together, either via creating incentive mechanisms for them to get exposed to each other or by creating joint gathering grounds where boundary objects between disciplines can be formed as their focus of research.

Preliminary efforts that contribute to both these directions are already being carried out by members of all the relevant stakeholder groups. One example from government funding schemes is a recent BMBF grant in Germany titled “Quantum technological and photonic system solutions for challenges of environmental and climate protection, biodiversity, sustainable energy systems and resource conservation” [99], where research not on QT but with QT on other research topics is exclusively targeted. Tailored funding schemes such as these will necessarily require the formation of consortia consisting of parties from different disciplines. Successful project implementation will depend on extensive co-learning within these consortia. International versions of these, such as those via the Horizon program or the bi/tri-lateral research agreements between different countries, similar to a recently announced one between France, Germany, and the Netherlands [100], can contribute greatly to allowing the exchange of expertise between borders as well. An example from industry stakeholders is Deloitte’s Quantum Climate Challenge [101] organized since 2021, where Deloitte aims to drive impactful, climate-relevant collaborations between sustainability and climate professionals and quantum computing experts. Similar efforts from different industry stakeholders can also be found, such as the Airbus BMW Quantum Computing Challenge focusing on utilizing quantum computers to forge more efficient, sustainable and safer solutions for the future of transportation. There are also examples consisting of collaboration between multiple stakeholders, such as the formation of the Open Quantum Institute (OQI) [102] and the launching of the XPrize Quantum Applications [103]. OQI is an initiative launched by GESDA (a Swiss NGO), partially supported by the Swiss government, passed along to CERN for operational purposes. XPrize Quantum Applications is a global competition launched by XPrize, Google Quantum AI, and GESDA with a $5 million prize designed to generate quantum computing algorithms that can be put into practice to help solve Sustainable Development Goals (SDG) related problems. Both of these examples focus on using quantum computers for purposes beyond quantum computing research, and both are collaborative efforts between multiple stakeholders of the quadruple helix.

Although the schemes introduced above also help the efforts towards the creation of boundary objects between disciplines, some early examples of boundary objects already exist in the field and can be studied to understand how such objects form. One such object, termed a 'post-quantum signature,' within the intersection of QIS and cryptography is exemplified by the Merkle signature scheme. This scheme, introduced in 2006 [104], was identified as having "a good chance of being quantum computer resistant" at that time. Its significance lies in being the first and most effective one, as it later kickstarted the field of post-quantum cryptography (PQC), resulting in an 8-year long competition by NIST [105] to determine the most suitable PQC algorithms and a declaration by the White House in August 204 that the transition to PQC is estimated to cost U.S. federal agencies $7.1 billion by 2035 [106]. Similarly, another successful boundary object between QIS and computer science, arguably the closest ‘outside’ discipline to

QIS following physics, is called ‘a quantum-inspired classical algorithm.’ The first example of this appears in the literature in 1996 in the Proceedings of the IEEE Conference on Evolutionary Computation. There are around 1000 articles and proceedings published in WoS indexed sources with the explicit keyword of “quantum inspired” as of August 2024.

As explained in the introduction of this section, neither of these approaches can be expected to fully prevent emergence of a quantum divide in science. However, adoption of these directions can both soften the potential disadvantages of a deep divide, make building bridges over it easier, and overall distribute the benefits of having technological access to the quantum world to disciplines and the pursuit of knowledge in fields beyond quantum mechanics and physics in general. As introduced above, all the different stakeholders of the quadruple helix have options to take action on their own or collaborate with other stakeholders within their innovation ecosystems.

B. Navigating the Quantum Divide in Technologies Through Path-dependency

In the relevant subsection II.A.II, we introduced a potential quantum divide in technologies that may emerge at the point of lock-in [67]. This divide is anticipated not only between countries but also within the techno-economic paradigms [7], with distinct options forming around various dominant modalities, particularly for quantum computers and networks. Such a divide will affect all innovation ecosystem actors who might find themselves on different ends of the spectrum in terms of their involvement with the final dominant modality and system designs.

The way to mitigate the negative impacts of such a divide emerging would be to diversify one’s portfolio of investments. However, this is not a task for those who cannot afford diversification and are forced to choose their bets carefully. There are certain actors in the field who can abstract themselves away from this or that modality, focusing on device-independent models of software development approaches or applications that can run on any type of quantum computer. Although this is usually accepted as a good alternative to diversifying for those accepting to not compete in certain aspects of QT (i.e. quantum hardware), it still will not prevent the divide from emerging, as those with dedicated software approaches customized for the final dominant design will have an advantage over those that were hedging their bets.

There is a nuanced point here regarding the future of QT platforms. The potential for this type of divide—where a "winner takes all" scenario leaves others with substantial sunk costs and little to show for it—may lead the entire ecosystem to lock into a technically sub-optimal modality. This risk is particularly high in areas such as energy efficiency, where most players are currently not optimizing their approaches with respect to. The race to deliver any kind of advantage useful for industry purposes motivates the actors not to diversify but concentrate their research and development efforts on already laid tracks. Developing an industry-scale quantum computer is costly and expensive even for the largest commercial actors in the field, such as IBM, Google, and Microsoft, or developing infrastructure-worthy quantum network devices for actors such as IDQ/SK Telecom and Toshiba. The required speed and intensity of investments into these endeavors to deliver outcomes force the hand of these actors to entrench themselves into supply chains and workforce skillsets most suited for the technological path they are most

invested in. It is true that "…*the space of the technologically possible is much greater than that of the economically profitable and socially acceptable*" [7, p.186], but it is also true that there are technologically possible innovations which are economically profitable and socially acceptable enough to kickstart a virtuous cycle without being the best option technically. This becomes irrelevant after a certain lock-in point; for example, the trillions of dollars already invested in silicon-based transistors make it practically impossible to switch the entire computing industry to an alternative platform for classical computation, a similar switch that took place in the 1950s from the vacuum tubes to silicon transistors. However, in the field of QT, we are still in the early stages of development. Somewhat paradoxically, the way to prevent this outcome is to slow down the commercialization race, not stifle it, but make it into a marathon rather than a sprint [107] and focus on exploring the opportunity space of possible technologies further. This, of course, will not prevent the divide from emerging between those who are more heavily focused on the final dominant modality and design compared to those heavily invested in another modality with a completely different design. Nevertheless, it will lower the entry barrier to the race and expand the base of those who can afford to diversify. In the end, if we are allowed to abuse the racing analogy, more people can afford to participate in a marathon than a sprint race, and it is not really a big deal to not be the first person to finish a marathon compared to a sprint race.

This is one of the cases we mentioned earlier, where it is in favor of the vested interests of some stakeholders to actually widen the quantum divide instead of narrowing it. Governments and investors that prioritized certain modalities over others and companies developing particular types of quantum hardware would actively benefit from the emergence of this divide and can benefit immensely if it is a wide one. In a plan of action by any of the stakeholders, this conflict of interest should be acknowledged and considered. Bridging this divide via such a diversification introduced above increases the necessary amount of investment into QT to enable exploration of the technologies opportunity space but will result in a more optimal and better dominant design that is also more equitably accessible.

C. Navigating the Quantum Divide in Between Countries

In subsection II.A.III, we explored two possible causes for a quantum divide to emerge between countries; (i) how the countries position themselves with respect to other countries and whether countries have technological or infrastructural access to prerequisite resources or not, and (ii) the factors/constraints countries have in their technology selection processes that differentiate them strategically. We primarily explored them through the lenses of self-sufficiency in relation to (de-)globalization [108], existing infrastructure and strengths of countries, the workforce shortage [82], and the corresponding topic of international labor mobility in QT [87]. Out of the four types of divides we describe, this is probably the one that is actually desired and aimed for by a considerable number of actors in the geopolitical arena. Therefore, we believe it is the one that is most likely to emerge strongest and has the most negative impact on those on the wrong side of the divide.

This divide poses unique challenges when considered alongside the other divides within the quadruple helix framework. While the scientific, technological, and societal divides directly align with the stakeholder groups of academia, industry, government, and civil society, the

country-based divide operates on a broader scale that often includes actors outside these defined helices. For example, within the United States, governmental agencies involved in quantum technology development fit well into the governance dimension of the quadruple helix. However, the divide between countries such as the US or EU member states and smaller ones demonstrates the limitations of the framework in fully capturing the complexity of global dynamics.

This complexity reflects the nature of the country-based divide as one that extends beyond institutional relationships to encompass disparities between entire nations. While some countries benefit from structured innovation ecosystems embedded in the quadruple helix, others lack the capacity or infrastructure to engage at comparable levels. Despite this, it is important to note that divides also exist within nations, where varying levels of investment, collaboration, and strategic alignment among governmental bodies can mirror the challenges seen between countries.

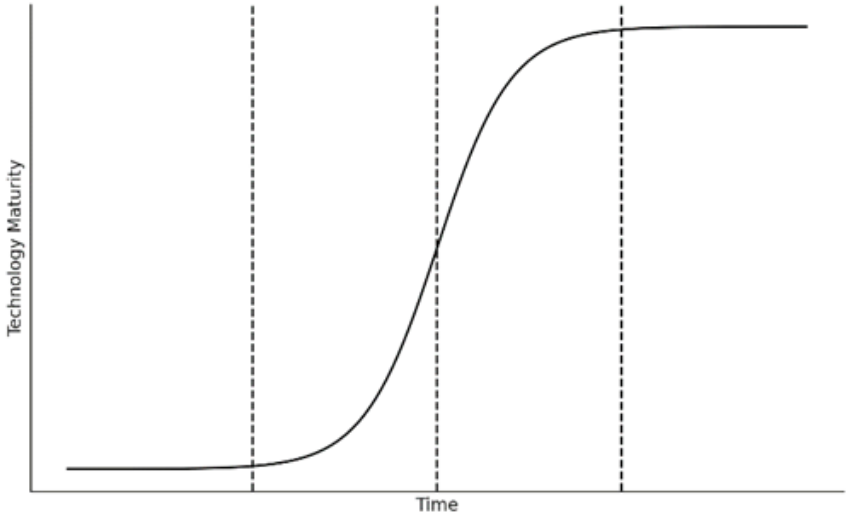


Fig. 4: Four phases of technology maturation over time

We will argue for three ways to navigate this divide, but this time they are mostly incompatible with each other. The first one comes from the argument on the small players taking big risks [81]. It is suggested that the small players still have the opportunity to make a significant impact by identifying a specific area of focus that includes originality and high risk, not becoming consumers but creators by taking the risks that bigger countries did not take. This is not a new argument; it actually ties neatly back to the argument of running in a new direction [6] in the (techno-) economic catch-up literature. Through their work in years, developed in the 1980s and 1990s, authors such as Perez, Soete, Dosi, and others identified that for a following country to be able to catch-up to the leading country in a techno-economic paradigm, there are two primary windows of opportunity.

The easier one to identify is the fourth one, when a techno-economic paradigm is matured, where only incremental improvements are possible (see Figure 4). This creates a period during which new investment into developing a technology further becomes more and more expensive while the return on investment is getting lower and lower, allowing the following countries to

compete with the leading country on grounds outside of technical superiority (like labor or land). The second window of opportunity, which is not so obvious, is during the period of a techno-economic revolution, where a following country can choose to run in a new direction and stop following the leading country which is just continuing to make investments into developing a mature techno-economic paradigm to be more productive, getting less and less return on their investment. The argument on small countries taking on risks of running into a new direction which the more established ones are not exploring might actually provide highly beneficial outcomes for them given that they run in the right direction or at least a direction that is good enough to guide through the technological revolution. One successful example of this occasion can be argued as the case of Taiwan and TSMC. The difficulty is that it is not easy to identify such directions, while there are so many different directions that only lead to dead ends with considerable sunken costs.

The second way that can be followed to navigate this divide is to not compete in the race, fail, but fail successfully. Not aiming to catch-up to a techno-economic leader but only aiming to increase the overall prosperity of a country can also be considered as a worthy endeavor. Yet, it would require explicitly accepting the chance of missing out on a valid window of opportunity for technological leapfrogging. It involves acknowledging the role of not becoming creators but mostly consumers of what the technological revolution brings forth. Foregoing the aim of being an early adopter or an early majority, when done intentionally and successfully, this can mitigate the most negative impacts of a quantum divide between countries.

The third way is to team up, especially with regional or established trade partners. A report published by QuEra in July 2024 on survey results of 927 participants from the QT ecosystem titled “The Current and Future State of Quantum Computing” [109]. In which they ask, “*How important is it for your organization where the quantum computer was developed?”* as one of the survey questions. According to their report [109, p4] 27% of the respondents replied that it is important that their quantum computer should be developed in their own country, while 45% of the respondents replied as it is important that their quantum computer should be developed in a country which is a friendly trade partner. This can be used by both the countries on the disadvantaged end of this divide and the countries on the advantaged end of this divide. Ideally, it can be used to match countries from both ends. A good example of this is the EU’s QuantERA and Quantum Flagship initiatives, which support quantum research across 31 European countries. When accounted for separately, the countries with the most start-up and commercialization activities in QT are the US, Canada, and the UK. However, when EU-27 is calculated as a single unit, the number of start-ups is on-par with the US for the top spot [75] and the total amount of investment is almost equal to the advertised amount from China. Infrastructure projects such as EuroQCI and EuroQCS cover several countries in the EU, aimed at spreading the QT infrastructure. For example, the six new EuroHPC quantum computers that are going to be integrated into existing supercomputers are located in Czechia, France, Germany, Italy, Poland and Spain, a combination of leading and following countries. Similar initiatives on all shades of this regional and trade partnerships are expected to increase, as there are ongoing preliminary efforts in this direction in regions such as the Association of Southeast Asian Nations (ASEAN) [110] and between allied countries like the US, Japan, and Republic of Korea [111].

We argue that all three ways introduced above are valid ways to deal with the expectation of such a divide emerging. However, it is important to note that these are incompatible approaches. If a country wishes to run in a new direction and try to leap-frog during a technological revolution, all the relevant stakeholders of the quadruple helix [8] of that country should be aligned with that goal. On the other hand, if a country wishes to 'fail successfully' in catching up in a manner that causes the least harm from the emerging divide, its relevant stakeholder communities should act in unison as much as possible. A half-hearted effort to leap-frog will most likely end in considerable opportunity costs, and a half-hearted effort to be a follower might end up causing the country to miss the train and only realizing it when they are very late to the party. Finally, if a collaborative effort is aimed to be put forward, all members should align their goals and priorities with respect to the joint efforts, one member aiming to fail successfully while another aiming to adopt a high risk- high reward approach may end up causing both to not succeed in their respective goals.

One final on this subsection is that identifying the way a country is aiming to navigate this divide is not a straightforward endeavor, as most countries won't have a singular focus on either of the three ways and different governmental agencies with different priorities might push for different ways to navigate. It is important for those with leadership and managerial positions of organizations within different stakeholder groups (such as universities, companies, NGOs, etc.) to keep a close eye on the signals coming from their government agencies on which policies to be pursued and how they are going to be implemented. This is essential for both the government level strategies to succeed and for the organizations in question to benefit from these strategies or at least minimize the harm they would suffer if the policies are designed in a way that are disadvantaging for some stakeholders (like a policy to 'fail successfully' would be detrimental for those already invested in QT startups in a country).

D. Navigating the Quantum Divide in Within Societies

As mentioned in subsection II.A.IV, this is the most highlighted type of divide in the literature, and multiple ways to mitigate the negative impacts and navigate have already been proposed previously. Increasing avenues of access via expanding the user base of these technologies is accepted as a necessary but not a sufficient condition for bridging this type of divide [27]. A renewed urgency to make quantum theory understandable [18], implementing a "strong" RRI approach which entails linking parliamentary or other core policy processes to stakeholder dialogues [30], increasing awareness on both the technologies themselves and their risks [112], creating a dialogue between innovators and societies [113], enabling participation via citizen science initiatives [85], forming and supporting grassroots communities, promoting outreach activities [27], and having value sensitive design practices embedded in the QT development processes [114] are only some of the recommendations made in the literature. However, these discussions are still in their infancy, with only several dozens of articles published on anything related to social and QT as of 2022 [115].

Furthermore, there is a growing number of governance framework proposals in the literature in recent years [27], [116], [117], [118]. The common point of all is the inclusion and empowerment of societal stakeholders, bringing the public up to speed on what QT can deliver, what it cannot deliver, and the wisdom to know the difference. Of course, depending on the theory of

democracy one abides to (i.e. participatory, deliberative, or representative [27]), this process can take different forms. For example, in the case of a participatory model, co-creation activities and citizen science approaches might prove to be more essential, compared to a representative approach where civil society organizations and different communities within QT formed as bottom-up initiatives [114] can act on behalf of the societal groups they represent. In terms of a deliberative model, having public dialogue options available where societal stakeholders can connect to these technologies on their own terms [94], [119] would be a good first step to involve them into the deliberation, though requiring many more steps for a truly democratic process.

E. Interconnectedness and Distinctness of Divides

The four divides—scientific, technological, geopolitical, and societal—are not isolated phenomena but interconnected challenges that influence and shape one another. As it is obvious at this point to our readers that there are many overlapping aspects of the different divides we described, there are reinforcing qualities between them where the emergence of one type of a divide increases the probability and potential severity of the other types. There are distinct scenarios as well, where certain types of divides might emerge but not others. For instance, the scientific community could prevent the full emergence of the quantum divide in science by implementing strategies such as intensifying efforts to establish collaborative research infrastructures, actively fostering connections among diverse research communities, and employing other measures. The technology development process might be intentionally (or due to external reasons) slowed down considerably. This can prevent the emergence of a full-blown quantum divide in technologies by giving the relevant actors enough time to phase out of their sunken cost investments and re-orient their resources to join the ecosystem forming around the to-be dominant modality and system design. Countries may decide to give up pursuing a strategic and economic edge through QT, because they might lose faith in the technology or some other possible but less likely alternatives, such as adopting an equitable development model between countries, which should, in theory, prevent the rise of a quantum divide between countries.

While each divide arises from distinct dynamics, their overlaps create opportunities for more comprehensive strategies. A quantum divide in technologies would make investments made towards the ‘wrong’ technology into sunken costs. In practical terms, smaller countries that took risks the larger ones avoided [81] would find themselves not only lagging behind but also heavily committed to a path that most ecosystem stakeholders did not embrace. Such a situation puts a country at a significant disadvantage in the divide between countries. A quantum divide within societies might have an impact on research communities as well. Researchers from fields outside of the immediate vicinity of QIS will have less exposure to QT. Even this limited exposure will be obscured by narratives that present quantum mechanics as incomprehensible [18], further exacerbating the problem of a growing discrepancy between those research communities with access to revolutionary tools and those that do not have a clear understanding of the actual qualities of these tools because their information channels are distorted by narratives mystifying the technology. A quantum divide between countries, when combined with the global mobility of highly educated and skilled labor in the field, could deplete developing economies of their limited number of topic experts to the extent that only a few nations can effectively translate the technical language of QT into a format understandable by the public.

This situation can deepen the quantum divide within societies, as the ability to bridge the gap between technical aspects of QT and societal understanding becomes concentrated in a limited number of countries.

By framing the divides as interconnected rather than isolated, the discussion highlights the advantages of an integrated perspective. This approach emphasizes not only the challenges of managing each divide but also the potential for coordinated solutions that navigate multiple divides simultaneously. However, the interconnectedness and distinctness of different types of divides described in this work call for further attention than we can afford in the context of this article. They present opportunities and risks that are not apparent from investigating only a societal, country-level, scientific or technological divide caused by the widespread introduction of QT. The interconnected scenarios also call for navigation strategies considering multiple dimensions at once. This adds further complexity to an issue with already considerable complexity. As the navigation ways proposed in subsections III.A and III.C are clear examples, there are complementary approaches, and there are incompatible approaches regarding the navigation of different types of divides. When considering multiple dimensions, one must also investigate the impact of navigation strategies on other types of divides. If a country adopts a way to mitigate the potential negative impacts of a quantum divide between countries which is incompatible with an approach aimed at navigating the emerging societal divide, then further investigation and deliberation between stakeholders on priorities becomes an urgent issue to handle before taking action.

IV. Conclusion

In this paper, we aimed to elaborate on the possible divides that could emerge with the development of QT and bring a new perspective on the understanding of how to navigate these divides. We suggested that several types of divides can be formulated. The focus of our study included four divides emanating from the quadruple helix model of innovation, which are the quantum divide in science, the quantum divide in technologies through path-dependency, the quantum divide between countries, and the quantum divide within societies.

Our analysis began with the ‘scientific divide,’ where we explored how variations in knowledge and resources within the scientific community might lead to disparities in capabilities and opportunities among scientists. This divide underscores the importance of ensuring equitable access to QT knowledge and resources within the scientific arena.

In the realm of technologies, we delved into the concept of path-dependency [16], highlighting how the decision-making process in technology development can lead to certain technologies dominating, thereby potentially excluding others. This creates a competitive landscape where the choice of technology becomes a critical determinant of success or obsolescence.

The divide between countries, perhaps the most geopolitically significant, was examined through the lenses of technological and infrastructural access, self-sufficiency motivations, and strategic positioning in the global landscape. Our findings suggest that the quantum divide is likely to reinforce existing geopolitical and economic disparities, with significant implications for international relations and national strategies.

Within societies, we addressed how QT might perpetuate and deepen the digital divide, transforming it into a quantum divide. This divide is not just about access to technology but also encompasses the ability to understand, utilize, and benefit from QT. The interplay of QT with social structures, norms, and values underscores the societal implications of these emerging technologies.

TABLE II: Types of Divides and Associated Navigation Directions Provided in this study

Type of Divide	**Navigation Options (Non-Exhaustive)**
Scientific	1. Prioritize and support QT adoption in research fields outside of QT. 2. Encourage interdisciplinary collaboration with the QT field.
Technological	1. Diversify investment portfolios to mitigate the negative impacts of the eventual technology lock-in. 2. Slow down commercialization to explore technology options, lower entry barriers, and give time for ecosystem actors to adjust.
Country-level	1. Identify high-risk, original areas for follower countries to become creators, not mere consumers. 2. Choose to fail successfully, not competing in the race to catch-up. 3. Collaborate regionally or with trade partners to balance the quantum divide.
Societal	1. Enhance access and stakeholder engagement in QT. 2. Apply varied public participation governance frameworks.

We discussed that bridging all these divides simultaneously is not likely to happen, and investigation of possible ways to navigate these divides can prove beneficial for all the stakeholders of the quadruple helix, and their respective innovation ecosystems. In this regard, we proposed several ways to navigate these divides. Some of which are complementary and some of which are incompatible to be adopted at the same time, leading to different options and strategies that can be advocated and followed by those in leadership and managerial positions. A summary of these can be found in Table II.

As we know from the digital divide literature, having access is only a part of the game, and the importance of a technology is found in its integration into the production processes, its role in facilitating information exchange, and its support for engagement [31]. The emergence of QT will impact different stakeholders in a variety of manners; some will benefit from it, some will be just okay, and some will suffer from it. The distribution of these will depend on the paths taken by different stakeholders both within and outside of the QT ecosystem. Neither the benefits nor the harm of any emerging technology is distributed equitably, and the formation of a gap wide enough to be identified as a divide exacerbates this inequitable distribution. The list of navigation ways we proposed in this study is neither exhaustive nor it should be taken as a static list, especially considering that QT has a rapidly evolving landscape. It is essential to note that any way to navigate to be chosen by the stakeholders will require periodic review and updating depending on which of the potential paths in QT are being realized, and how the other

stakeholders are choosing and adapting their navigation strategies. It will be a constant game of positioning oneself with respect to others who are themselves with respect to others as well. Exciting times are ahead regarding QT, and it falls on the ecosystem stakeholders to identify and implement ways to minimize the harm of introducing QT to society.

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