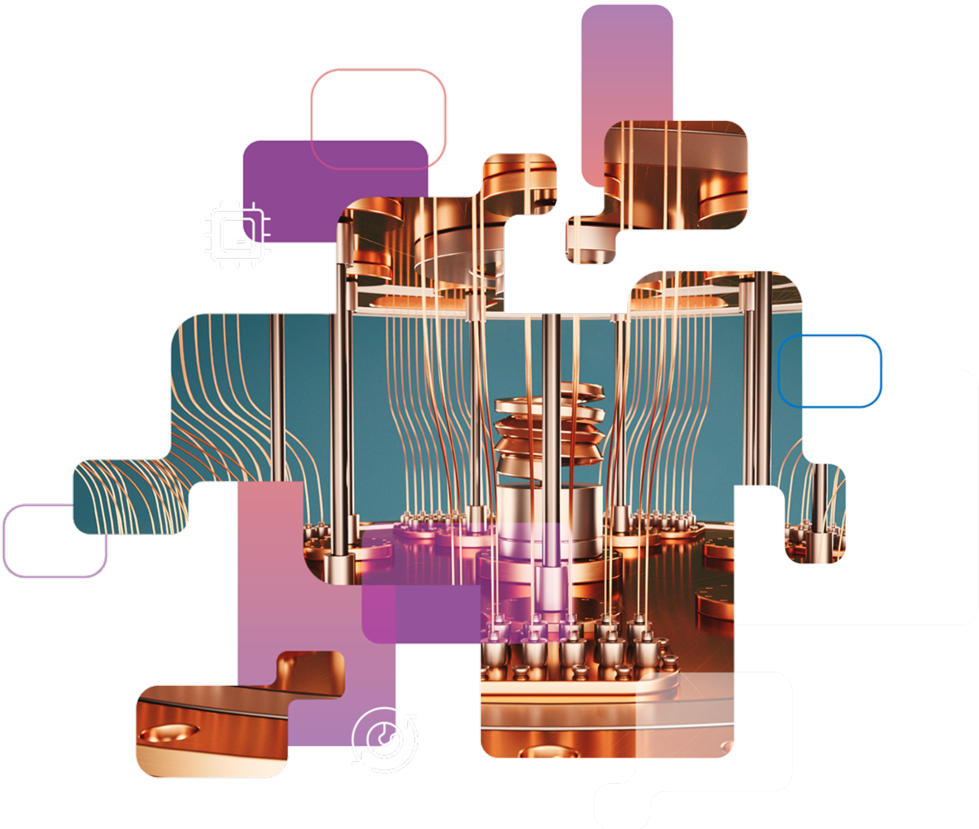
Driving innovation together

Preparing for a future with responsible quantum technologies

Understanding quantum technologies through a lens of responsible tech



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Management Summary

The development of quantum technologies (QT) comes with possibilities and risks. We need to start considering how and where we want to embed quantum technologies. Specifically, questions of security, access and uncertainty need to be addressed. QT can be used both for good and bad. In the field of security, for example, it brings means of breaking down data encryption, but also new ways of secure communication. Because of this dual-use nature of QT, ownership is an important topic. Who can/should access this technology is both a question of security and accessibility. Such questions require us to think about QT in the context of ethics and responsibility.

Preparing for a future with QT means preparing for the impacts that it will have. While uncertainty is still present, some of these impacts are known. Therefore, we can start translating the impacts into actionable processes. While security seems to be the main aspect of concern, there are also specific impacts for the fields of research and education that should be considered. How does quantum impact existing scientific practices and norms, such as reproducibility and openness? Migrating part of the computational infrastructure from classical to quantum requires new knowledge and experience. There is a need to educate or facilitate the people that are currently in the fields of cryptography and information security and prepare our current systems for a migration to different forms of encryption.

Overall, there are a lot of questions to be answered on how we will integrate quantum technologies in society. The fortunate thing is that there are people and organizations chipping away at these questions. Slowly, the assessments that come from these organizations need to be translated into concrete encryption systems and computational infrastructure. We still do not fully know how quantum will be integrated into society, research and education, but we are preparing for what we do know.

Introduction

Why Responsible Quantum

Quantum technologies (QT) are on the rise. Every year brings new benchmarks/achievements in their development. The Dutch government considers QT as part of the 'key technologies' in the Dutch innovation sphere (sleuteltechnologieën).[1] Developments in QT are surrounded by large promises such as IBM working towards significant scale-ups in quantum processors[2] and projects working towards a quantum internet infrastructure.[3] These developments come with excitement, but there are also concerns about the societal impact by this technology. This includes a quantum computer's ability to crack encryption protocols,[4,5] uncertainty around how soon these technologies will be available, and questions around ownership and sovereignty. These concerns require thinking about the impact of quantum technologies on a non-technical level.

Technical developments in quantum are rapid.[6] With these developments, there is a need to start discussing their societal impact and start formulating visions and aims. This requires considering not only the technical aspects but consider the technology in a broader scope. A way to start deliberation about these questions is through a lens of responsible tech. Responsible tech is "a way to align the ethical deliberations around emerging technologies with the existing challenges described in discussions about public values and ethics".[7]

Quantum technologies is specifically interesting compared to other emerging technologies. How the technologies manipulate particles at the smallest scale we can describe is fascinating, but also in its use and application there are novel aspects. One such thing is that, while the existence of the technology is quite well-known, practical experience with QT remains limited. In other emerging technology fields, such as AI, first-hand experience is easy. These technologies have become more accessible over the last years, meaning that they have embedded themselves more in society. Quantum technologies have not experienced such widespread use. Through this, and because quantum is still considered through its mathematical complications, their applications remain somewhat opaque.

Specifically for SURF it is relevant to understand how these developments impact research and education, and to what extent and in what timeframes should we be concerned about these developments? Therefore, the aim of his report is not to provide a complete understanding of what quantum technologies will or will not be capable of. Such literature is already located elsewhere, and the report will refer to these places when relevant. Instead, the aim is to start applying this existing knowledge to the impacts on fields of Research and Education specifically.

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[1] (van Bree et al., 2023)

[2] https://www.science.org/content/article/ibm-promises-1000-qubit-quantum-computer-milestone-2023

[3] https://quantumdelta.nl/qcined

[4] (De Wolf, 2017)

[5] https://www.nos.nl/artikel/2513219-quantumcomputer-gaat-computerbeveiliging-kraken-zorgen-nemen-toe

[6] https://www.surf.nl/quantum-computing-voor-onderzoek-de-stand-van-zaken, https://www.surf.nl/files/2023-02/sf_trendrapport_v10_compressed.pdf

[7] (SURF, 2023)

When Quantum Technologies will eventually leave the lab, we need to make sure that organizations that will be affected by them are ready to start working with them.

This report will provide technical knowledge where necessary but remain focused on the impacts that the technology will have. Therefore, a brief description on the novel properties of QT will be the point of departure. After this the report will illustrate how these applications lead to specific societal impacts. Again, the aim is not to provide a full understanding but create the necessary understanding both in the technical and the ethical to set the stage for further deliberation.

Contents of the Report

The content of the report is structured as follows:

(1) Create a baseline technical understanding about quantum technologies.
(2) Translate the technical capabilities from quantum technology into the societal impacts that these technologies will have, both in general as well as in education and research specifically.
(3) Introduce the fields that are already working on the topic of responsible quantum technology.

1 Understanding Quantum

Quantum technology is not a singular technology, but instead covers a set of multiple technologies. Quantum Technologies exploit the phenomena described by quantum mechanics to build devices with novel capabilities. Certain established technologies, such as MRI scanners, semiconductors and nuclear energy can be classified as quantum technologies. For the last 10/20 years, however, the world has turned their eyes on a new generation of quantum technologies. These technologies exploit the behavior of particles at the quantum scale to create novel technological devices.[8] The following sections will provide an overview of this new generation of QT.

1.1 Quantum Technology (QC, QS & QN)

In the 2023 revision of TNO's report on 'sleuteltechnologieën', a segmentation is made between the fields of quantum sensing (QS), Quantum Computing (QC), and Quantum Networks/Communication (QN).[9] These three subfields are established as separate research and engineering fields. All three are quite clearly defined as technical innovation fields,[10] but also have distinct discourses and impacts in the Ethical, Legal and Social Aspects (ELSA).[11] The following sections will shortly describe each of these subfields.

Quantum Sensing (QS)

Quantum Sensors are the set of technologies that improve upon classical sensors accuracy and sensitivity by measuring effects at a quantum scale. Quantum sensing is a field that covers more than one type of sensor. Their applications include "Measurement of magnetic fields, electric fields, gravity, temperature, pressure, rotation, acceleration, and time".[12] One specific application is the detection of gravitational fields at such a small scale, that it allows satellites to detecting the mineral composition of planets.[13] QS technologies are the most mature of the three QT subfields as their components are commercially available and their near-term applications are known.

While these applications are significant for specific data-collection fields, their impacts seem manageable. We can look at their classical counterparts and ask, "what would happen if these technologies were slightly better". Because of this, their impacts are more understandable than in QC and QN. This does not mean that we should disregard their impact, but instead we can look at them through the lens of other topics. The questions we should ask about the impact of QS can already be found in debates on large-scale data collection.

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8 (Dowling & Milburn, 2003)

9 (van Bree et al., 2023)

10 Ibid.

11 (Hoofnagle & Garfinkel, 2021)

12 (Hoofnagle & Garfinkel, 2021, p. 7)

13 https://www.nasa.gov/earth-and-climate/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry/

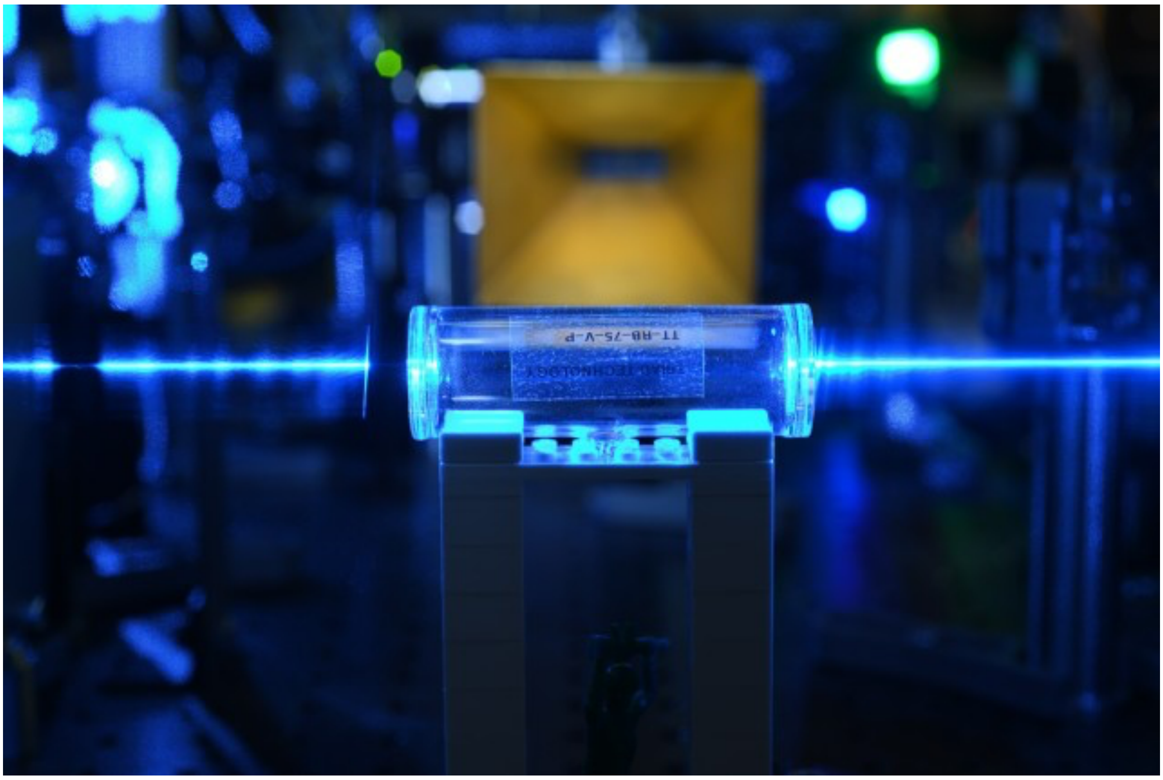

Figure 1: Quantum Sensor detecting electric fields.[14]

Quantum Computing (QC)
Quantum Computing is the QT most prominently featured in popular reporting on Quantum Technologies. Quantum computers operate fundamentally different from classical computers. The most fundamental object in a computer is a bit, which can be either a 0 or a 1. Quantum computers operate with qubits, which have more complicated behavior. Understanding this complicated behavior (which is often described as "the bit can be anything between 0 and 1) is not necessary to understand the impacts that a quantum computer will have. It is sufficient to know that a fully operating quantum computers can do some calculations better than a classical computer (as well as the other way around).

When one reads about a breakthrough in quantum technologies it often concerns a new benchmark in computational power or the number of qubits. Large organization such as IBM, Google, and Microsoft are developing Quantum computers, but alongside this, Dutch organizations, and startups such as QuTech, QuiX and QuantWare are also players in this industry.

There are several resources with intuitive descriptions on what makes quantum computing different from classical computing.[15] In short, quantum computers can perform certain

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[14] U.S. Army CCDC Army Research Laboratory Public Affairs, March 19, 2020. https://www.army.mil/article/233809/army_scientists_create_innovative_quantum_sensor

[15] I recommend the Quantum Vision Magazine on Quantum computing from TUDelft's Quantum Vision Team. https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-internet

computational actions in a significantly more efficient than classical computers. A common misunderstanding is that Quantum Computers will outperform classical computers in every way. This is not the case; QCs bring a new and different computing paradigm based on the properties of particles at a quantum scale. One can compare its functioning and impact as similar to the field of High-Performance Computing, and therefore operating it will likely be similar to these fields. The specific capabilities of QC will provide possibilities for new and more efficient computing applications. When QC will be developed enough to outperform its classical counterparts, it will likely be used in the fields of biology, chemistry, and material sciences.[16]

Figure 2: IBM Q quantum computer in 2018[17]

Quantum Communication/Quantum Network (QN)
Quantum Networks are a collection of multiple technologies that allows for connectivity between different quantum devices or between quantum and classical devices. Understanding QN as a technology requires us to think about technology similarly to how we consider the internet. The physical internet consists of networks, routers, receivers, senders and all sorts of interacting devices. A quantum network will be a similar system of devices that allows for a new way of encoding and sending information.

Like the QC, there are plenty of places with intuitive descriptions on what makes QN different from a classical network.[18] There are several stages in the construction of a quantum network that allow for different applications, ranging from secure key distribution to solving problems in

[16] (Hoofnagle & Garfinkel, 2021, p. 9)

[17] IBM Q Quantum Computing MIT Technology Review Innovation Leaders Summit, 30 November 2018, Pierre Metivier (cc-by-nc 2.0) https://flic.kr/p/2eeu8bT

[18] I recommend the Quantum Vision Magazine on Quantum Networks from TUDelft's Quantum Vision Team. https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-computing

distributed computing.[19] This means that, during the construction of a quantum network, there will likely already be several applications available before it reaches full functionality. Some specific applications include that it "creates fundamentally stronger encryption keys and may enable end-to-end data transmission with quantum states".[20]

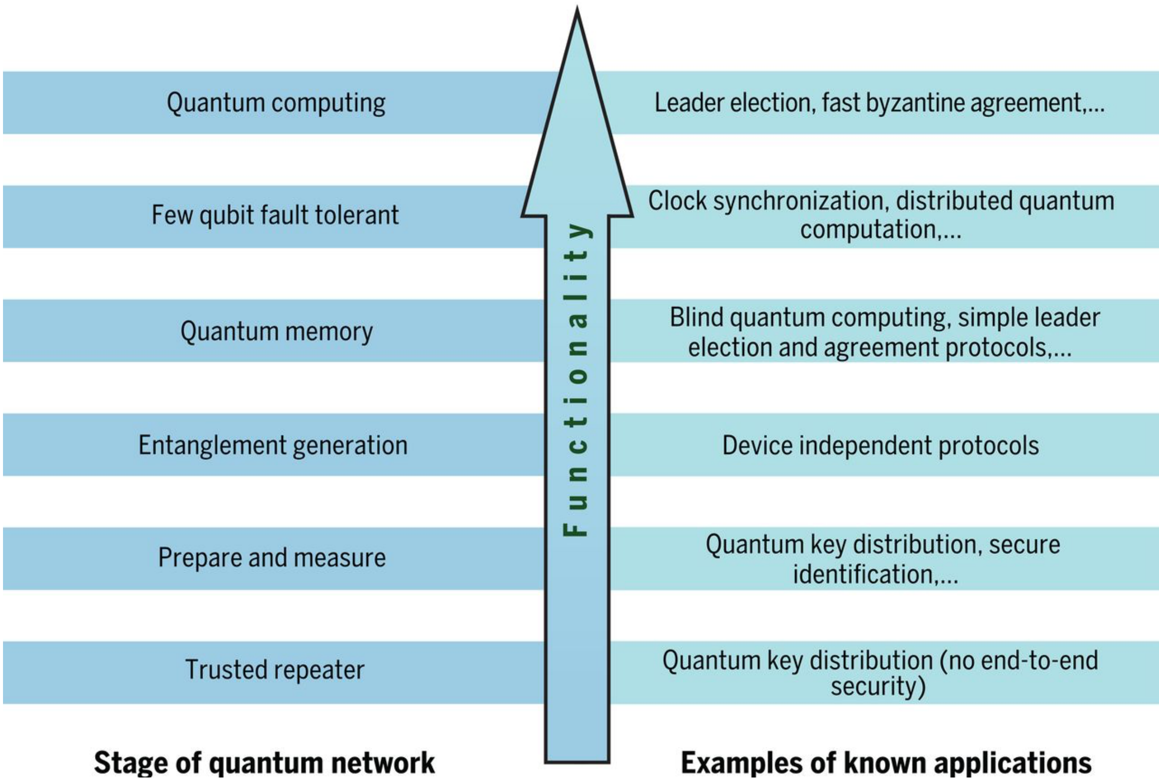

Figure 3: Stages of development in a Quantum Internet (Wehner et al., 2018)[21]

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[19] (Wehner et al., 2018)

[20] (Hoofnagle & Garfinkel, 2021, p. 20)

[21] https://www.science.org/doi/10.1126/science.aam9288

2 Anticipating Impact

In technology assessment one is often confronted with the notorious Collingridge dilemma.[22] The basis of this dilemma is that, when a technology is in development, there is no easy way of predicting its impact. Later, when the tech is developed and embedded the impacts are known, but being able to change or control the technology is much more difficult. This dilemma should not be seen as a discouragement to just accept the uncontrollable nature of technology. Instead, we should see the evaluation of and impact of technologies, such as quantum technologies as a continuous process.

For QT, these evaluation processes are already taking place at several layers of the academic, governmental and corporate spheres. This report outlines the most prominent impacts of quantum technology discussed within the various materials cited in this report.[23] The following is not a complete list of all the impacts that QT will have, but instead focusses on creating a set of impacts that are more prominent, illustrate the relevance of considering QT in a societal context, and topics that are most strongly related to research & education.[24]

2.1 General Impacts

Questions of Security

Out of all impacts that QT will have, security might be the most widely discussed. The most notorious application of quantum computers is Shor's algorithm. This algorithm is excellent at solving a specific mathematical problem which is used to secure data when transmitted between users. On a classical computer, this algorithm takes an unreasonable amount of time to do any meaningful calculation, but on a quantum computer they scale incredibly well. With a large enough quantum computer, Shor's algorithm can overcome one of the most widely used forms of encryption (RSA). Little imagination required to see the security problems that would arise from overcoming the most common form of data protection. On the 12th of March 2024, 20 Members of the European Parliament wrote a letter detailing precisely this problem.[25]

QT brings both challenges as well as opportunities to the security domain. The potential of Shor's algorithm creates a need for new standards in classical encryption that is resistant to future quantum algorithms. This is a major challenge in the current security paradigm. But QT also provide new abilities. Quantum Key Distribution (QKD) is a new cryptographic protocol which is resistant to the application of Shor's algorithm. To perform QKD, one would need a functional quantum network, which is currently not in place. Apart from QKD, there is work being done on alternative non-quantum algorithms that are resistant to Shor's algorithm (post-quantum cryptography). There are already several programs in place working on several paths forward. [26]

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[22] (Collingridge, 1982)

[23] Among others: (De Jong, 2022; De Wolf, 2017; Kop et al., 2023a, Kop et al., 2023b)

[24] For a longer, comprehensive, and digestible impact assessment of QT in general, I recommend the scan from Rathenau Institute (2023)

[25] https://www.computable.nl/wp-content/uploads/2024/03/Letter-MEPs-Post-Quantum-Encryption.pdf

[26] https://www.nccoe.nist.gov/crypto-agility-considerations-migrating-post-quantum-cryptographic-algorithms

Questions of access

Especially in its early stages, producing and maintaining QT will be costly and technically complicated. Therefore, broad accessibility to the technology is not a given. It is likely that a central party will host and distribute access to the technology. They are, therein, able to decide who gets access to this technology, and on which terms. For example, which research fields and groups should receive priority when it comes to computational resources and knowledge on the workings of Quantum Systems. Questions of access are also about security. Computations on a QC, for example, could be used for research and optimization, but also for malicious intent, such as breaking encryption. This touches on common discussions around key technologies and knowledge security, do we trust other parties to get access to certain capabilities?

What is unique about QT, compared to classical computation technologies, is the way in which it handles information. If a malicious actor has bad intentions, QC is particularly vulnerable due to the emerging field of *blind quantum computing*.[27] The fundamental physics behind qubits allows a quantum computer to perform calculations without retaining information about the process that was just performed on it. Due to the nature of information on a quantum system, measuring quantum states will disturb processing and is therefore impossible without interference. This makes it possible to do computation without the possibility for oversight, which is being called *blind computing.* Computation without oversight brings potential for secure processing of sensitive data, but also allows for untraceable malicious use of the quantum computer. Future owners of QC infrastructure will be confronted with this dual-use nature of the technology and the challenges in managing access.

Questions of uncertainty.

While certain applications in QS are ready for use, QC and QN are still in development. This means that, as of now, it is unsure when specifically, they will be mature enough to see implementation and what form specifically have. The quantity of work and money in the field is sufficient to see the technology develop further over the upcoming years, but as of now it is impossible to predict, for example, whether we will have a quantum equivalent to Moore's law.[28] Current Quantum computing systems, however, are notorious for their difficult operating conditions. Retaining a qubit in a stable condition requires a strongly controlled physical environment. As with most new technologies, optimization and scaling will improve over time, but to what extent we can make these systems energy efficient is not known. Similarly to other energy intensive computations, we should start considering this for quantum technologies.

Apart from uncertainty about the timespan and scale, there is also still the possibility for new developments in the quantum. Again, we can look at the classical computer and internet for what this specifically means. The computer and internet are impactful technologies because of the applications that emerged from them. Social media, instant text-messaging and simulated environments are all technologies built on a foundation of computers and networks. For the QC and QN we can consider it likely that new applications are to be discovered with their development.

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[27] (Broadbent et al., 2009; Possati, 2023)

[28] The historical trend where, from a certain point onwards, the number of transistors on a computer chip seemed to grow quadratically.

All these uncertainties require to adequately scope our expectations and predictions about QT. The field of quantum, due to the notorious complexity of quantum theory, is especially prone to narratives of grandeur and hype.[29] Other fields of applied physics, such as nanotechnology, have seen similar trajectories. Many were, at once, considered as potentially revolutionary and disruptive for fields such as medicine, electronics, and sustainability. Over time, however, these fields crystallized to a set of specific applications and embedded themselves within these fields, leaving a less large crater than once proclaimed. Uncertainty, herein, does not call for radical yes/no decisions in pursuing technology, but instead for adequate scoping.

2.2 Impacts in Research & Education.

The following sections illustrate how QT can impact research and education specifically.

Research

Quantum Algorithms/computations work in a fundamentally different way than regular computations. This difference in computation will mean new possibilities for research fields. To make use of these new resources, researchers and research supporters will have to learn to work with these systems. This requires educating the right people about the technology and its capabilities. Again, this brings forth questions about access.

- Who will be the ones to make use of these systems?
- To what extent can/should we be dependent on the services of larger providers?
- Which research fields will benefit the most from its applications?
- In what ways does Blind Computing influence the way in which we see data, calculation, and reproducibility in science?
- Which fields require thorough attention in their data security when it comes to possible information breaches?

Education

Migrating part of the computational infrastructure from classical to quantum requires new knowledge and experience. There are already movements towards education the new workforce in education. Courses on quantum encryption, or even full master programs in quantum technology are being developed.

Apart from creating the workforce of the future, there is a need to educate or facilitate the people that are currently in the fields of cryptography and information security and prepare our current systems for a migration to different forms of encryption.

[29] (Ezratty, n.d.; Grinbaum, 2017)

3 Towards Responsible Quantum Technologies

As of now, we have no definitive answers for the questions on responsibility in quantum technologies. The good news is that we do have the tools and knowledge to start chipping away at them. This final section aims to highlight some accessible tools and frameworks that can be used to explore responsible QT. This will be done through (1) highlighting general frameworks for ethical assessment of emerging technologies, (2) give some examples of frameworks that have already been applied to QT, and (3) provide some perspective on a responsible future of QT.

Ethics of Emerging Technologies.
As stated before, evaluating developing technologies is a continuous process. Therefore, it is worthwhile to see ethics and responsibility not as something that happens at one particular moment in time but consider it as an ongoing practice. This entails continuous reflection on the current situation, holding oneself accountable and involving stakeholders. These ideas, and specific tools for how to continuously reflect on how to integrate such processes are further developed in SURF's 2023 discussion paper on Responsible Technology.[30]

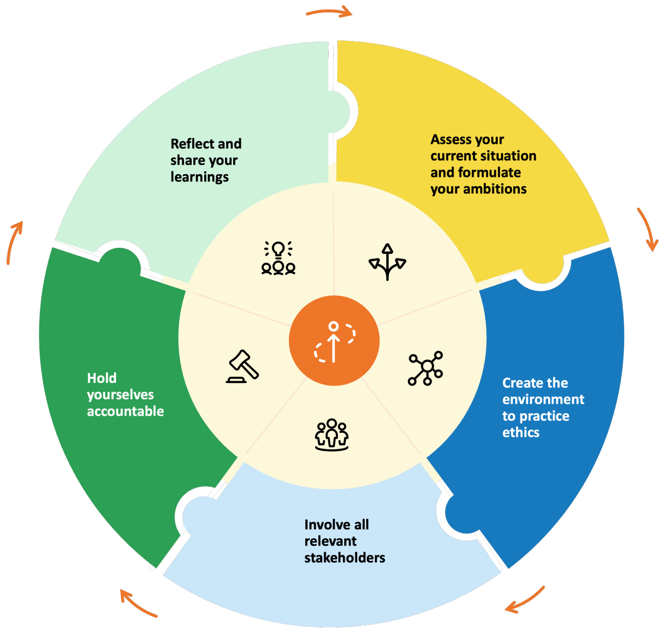

Figure 4 Responsible tech model (SURF, 2023)

As an illustration of a concrete activity for technology assessment, one can look at the Guidance Ethics Approach.[31] This approach aims at creating a baseline understanding of the technology from which different stakeholders can discuss the impacts and values. The aim of the approach is to use this interdisciplinary setting to create understanding between groups and then provide tools for working towards actionable principles. More of these tools can be found in the discussion paper.

[30] (SURF, 2023)

[31] (Verbeek & Tijink, 2020)

Ethics of Quantum Technologies

Early exploration of the ethics of quantum technologies was mainly an academic endeavor. Significant steppingstones in this research includes discussions on Responsible Research and Innovation (RRI)[32], principles for responsibility[33], and metaphysical explorations on how quantum data is ontologically different than classical data.[34] From this research we have pointers where to look for when thinking about responsible quantum technologies. Among other aspects, they highlight the relevance of open science, accessibility[35], societal understanding [36] and autonomy.[37]

These principles, luckily, do not just reside in the academic sphere. The Dutch quantum ecosystem also features nontechnical organizations that are working on the societal impact of these technologies. Examples of this include the Rathenau Scan on quantum technology in Society, which brings a digestible overview of the field of quantum and its impact. The scan looks forward on discussing quantum technology beyond the hype surrounding it. They state that quantum technologies are unlikely to be the revolutionary technologies that are sometimes proclaimed to be and expected from novel technologies. They plead for a “considered judgement on the impact of quantum technology”.[38]

Other organizations, such as the Centre of Quantum and Society, are working towards “better understand[ing] the societal effects of quantum technologies and inform the broader quantum community about these impacts”.[39] The activities in the ecosystem are about staying connected, but also features steps towards enabling other organizations to analyze the impact that quantum will have on their specific organization.[40]

Looking Forward

Overall, there are a lot of questions to be answered on how we will integrate quantum technologies in society. The fortunate thing is that there are people and organizations chipping away at these questions. Section 2 of this report shortly touched on the Collingridge dilemma, about the trade-off between timely assessment and changeability. To overcome this timeless dilemma means to focus on technology assessment as a continuous endeavor. We still do not fully know how quantum will be integrated into society, research and education, but we are preparing for what we do know.

The goal should then be to keep this going. That means staying connected, working openly on these problems, and reaching out for help when needs and questions arise. In this document I have referred to some of the written material that is available on these topics. The quantum ecosystem, however, is not just technology and publications, but it also consists of people.

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32 (Coenen & Grunwald, 2017)

33 (Kop et al., 2023a), (Kop et al., 2023b)

34 (Possati, 2023)

35 (Coenen et al., 2022)

36 (Vermaas, 2017)

37 (Rathenau Instituut et al., 2023)

38 (Rathenau Instituut et al., 2023, p. 22)

39 https://quantumdelta.nl/centre-for-quantum-and-society

40 https://quantumdelta.nl/news/quantum-delta-nl-launches-exploratory-quantum-technology-assessment-eqta

Partaking in this ecosystem will help with establishing expertise where needed, and therefore make our future with Quantum Technologies a better one.

Interested in more?

SURF Publications

- https://www.surf.nl/themas/kwantum
- https://www.surf.nl/en/themes/public-values/responsible-tech-this-is-how-we-ensure-new-technologies-meet-public-values
- https://wiki.surfnet.nl/display/AIML/What+is+Responsible+Tech

Whitepaper series on quantum technology; Lessons from AI

- https://quantumdelta.nl/news/white-paper-1-3-lessons-from-ai-stakeholder-engagement
- https://quantumdelta.nl/news/qdnl-white-paper-2-3-lessons-from-ai-communication
- https://quantumdelta.nl/news/qdnl-white-paper-3-3-lessons-from-ai-risk-management

Accessible magazine publications on quantum internet and quantum computation

- https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-internet
- https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-computing

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