Exploratory Quantum Technology Assessment

Direct the impact of Quantum Technology
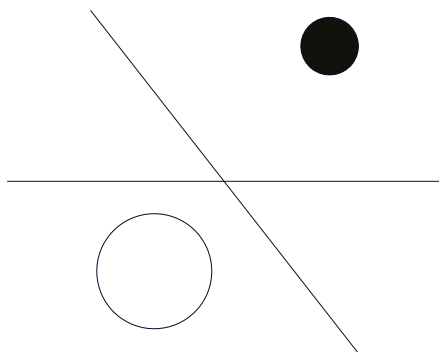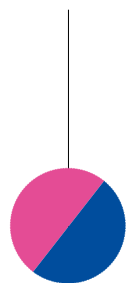
Quantum Delta NL

Exploratory **Quantum** Technology Assessment

A practical roadmap for organizations for exploring the societal, technical, legal, and ethical implications of quantum technology.

Quantum Delta NL

GOAL EXPLORATORY[1] QUANTUM TECHNOLOGY ASSESSMENT (EQTA)

Quantum technology is a key technology: it is an impactful technology that is increasingly becoming part of the products and services around us, of our computers, sensors, and networks. The opportunities this brings to society, economy, and science are significant, and quantum technology will be able to positively contribute to the challenges facing society.

Quantum technology is developing rapidly: some applications are already possible today, others will come to market in the coming years, and some will require major technical breakthroughs still. However, the direction of these developments is partly determined by the opportunities and application potential that organizations and society are aiming for. Thinking about the opportunities and possibilities, while timely creating the prerequisites for responsible application requires a focused effort.

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1   The word 'exploratory' was adopted because quantum technology is rapidly evolving, as are the circumstances affecting applications: think of the upcoming and ever-changing laws and regulations around security and privacy, data and cloud, the rapid standardization developments of quantum technology, and geopolitical developments.

The EQTA is a practical roadmap that helps organizations with this effort: by exploring the opportunities and impact of quantum technology in a timely manner, an organization can avoid negative impacts and set preconditions. This is required to ensure that opportunities and impact can be managed.

The EQTA is an instrument through which Quantum Delta Netherlands (QDNL), which combines efforts in the Netherlands around quantum technology, contributes to the optimal and responsible use of opportunities of quantum technology.

The EQTA supports two types of organizations:
• Organizations experiencing the impact of quantum technology now or in the future once quantum technology is increasingly adopted.
• Organizations developing or applying quantum technology themselves at present or in future.

The EQTA – Quick Scan and roadmap

**The EQTA begins with a Quick Scan that consists of:**
• Exploration of technology: what is it? A brief orientation on quantum technology and timelines. (See Appendix 01: *Quantum technology in brief*).
• Exploration of application possibilities: what is in store for the organization? A brief orientation of application possibilities using examples. (see page 30: *EQTA and Quantum Delta Nederland*).
• Brief description: based on the impression of application possibilities using examples, outline what impact the organization will experience from quantum technology and/or which of the applications are relevant to a specific organization.
• Brief stakeholder analysis: who are the important stakeholders/experts that will be impacted?
• Dialogue session: explore and test what is needed to make the most of the possibilities of quantum technology and, if necessary, avoid negative impacts (see page 15: *In practice - step 4 : Dialogue with stakeholders*).

Should the dialogue session reveal that action is necessary, organizations may then proceed through the entire EQTA to further explore specific areas (societal, technical, legal, and ethical).

Who is the EQTA for?

The EQTA is relevant to any organization that is impacted by application of quantum technology or is concerned with the (future) development and application of quantum technology, the opportunities it presents for the organization, and what is needed to responsibly realize those opportunities and avoid negative impacts. To explore the opportunities and consequences, societal, technical, legal, and ethical frameworks are involved. More specifically, this would include quantum application frontrunners, innovation managers, (Chief) Security Officers, (Chief) Information Officers, lawyers, and ethicists.

It is important to consider that while these audiences may take the initiative to go through EQTA, they will need — to properly consider the various interests and perspectives — to engage with various experts and stakeholders. For instance, management and administrators, the people who will have to work with the technology, and those organizations and individuals involved experiencing its impact. Some issues can only be properly framed by also involving service providers, technology providers, or scientists and experts in a specific field (think experts on the societal, technological, legal, and ethical aspects). Who are involved in the dialogue depends very much on the nature and impact of quantum technology on the organization.
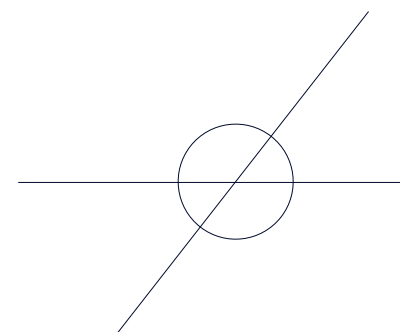
This dialogue is necessary because decisions around quantum technology often (will) require very complex considerations, involving the considerations and knowledge of experts from very different fields and stakeholders with very different backgrounds. Moreover, the uncertainties surrounding the technology must be considered while not losing sight of the organizational goals. The dialogue aims to ensure that those involved develop such knowledge and understanding of each other's perspectives that they can collectively devise approaches that do the maximum amount of justice to those perspectives (see).

The EQTA helps organizations to identify those various aspects and come to a decision — and justify that decision, then set up processes to evaluate those considerations and incorporate new information and insights.

"QUANTUM TECHNOLOGY IS A KEY TECHNOLOGY: IT IS AN IMPACTFUL TECHNOLOGY THAT IS INCREASINGLY BECOMING PART OF THE PRODUCTS AND SERVICES AROUND US."
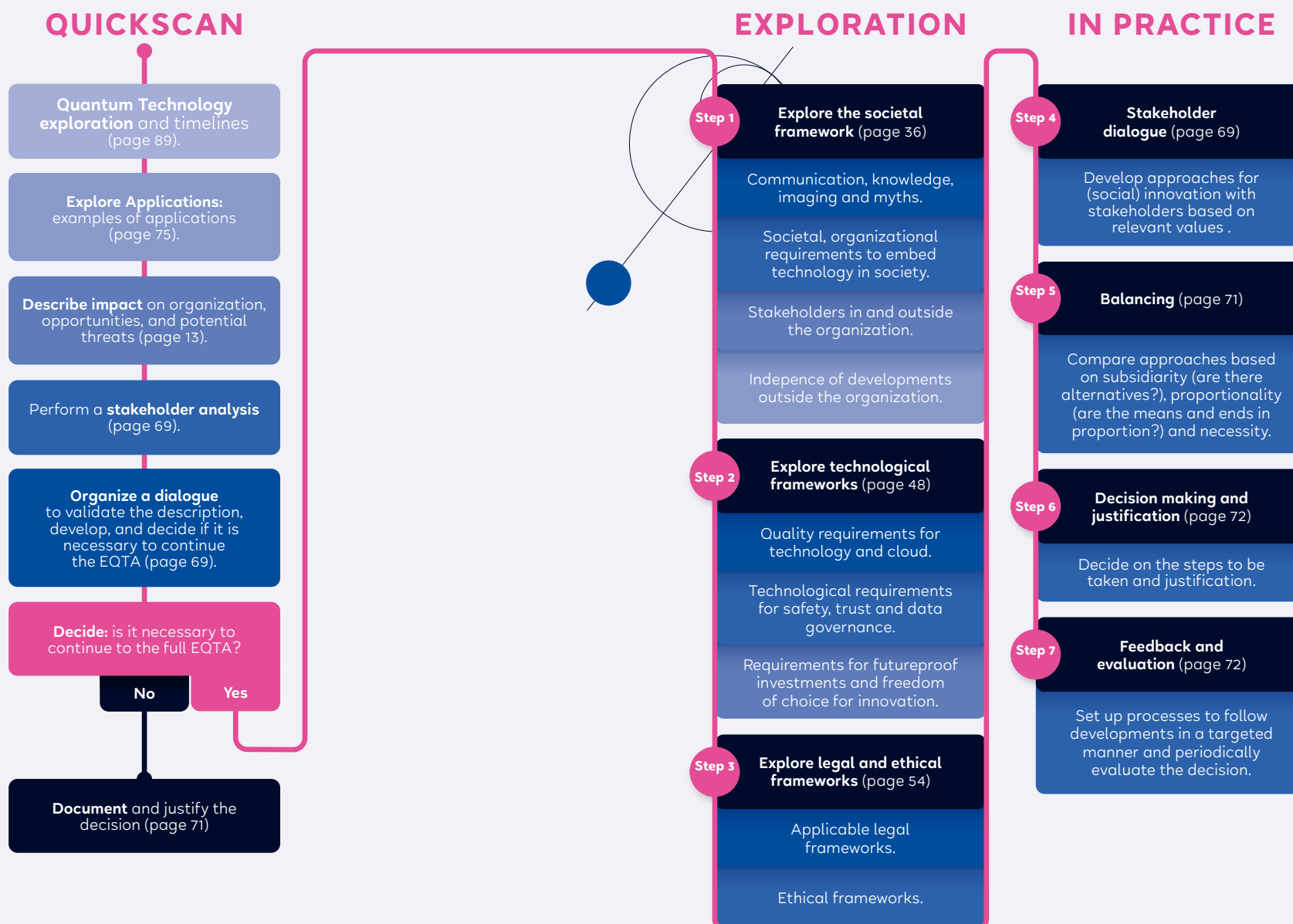
Quick Scan and roadmap

The EQTA helps organizations take the steps necessary for responsible application of quantum technology and to manage its impact.
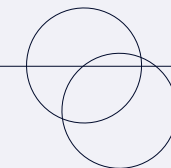
The Quickscan provides a quick overview of the points of attention to guide the impact of quantum technology in a timely manner.

If the quickscan shows that responsible embedding of quantum technology requires active guidance, then proceed to step 1 of the Roadmap.

If active guidance is not necessary, this decision is also documented.

QUICKSCAN

Quantum Technology exploration and timelines (page 89).

Explore Applications: examples of applications (page 75).

Describe impact on organization, opportunities, and potential threats (page 13).

Perform a **stakeholder analysis** (page 69).

Organize a dialogue to validate the description, develop, and decide if it is necessary to continue the EQTA (page 69).

Decide: is it necessary to continue to the full EQTA?

| No | Yes |

Document and justify the decision (page 71)

EXPLORATION

Step 1 — **Explore the societal framework** (page 36).

Communication, knowledge, imaging and myths.

Societal, organizational requirements to embed technology in society.

Stakeholders in and outside the organization.

Indepence of developments outside the organization.

Step 2 — **Explore technological frameworks** (page 48)

Quality requirements for technology and cloud.

Technological requirements for safety, trust and data governance.

Requirements for futureproof investments and freedom of choice for innovation.

Step 3 — **Explore legal and ethical frameworks** (page 54)

Applicable legal frameworks.

Ethical frameworks.

IN PRACTICE

Step 4 — **Stakeholder dialogue** (page 69)

Develop approaches for (social) innovation with stakeholders based on relevant values .

Step 5 — **Balancing** (page 71)

Compare approaches based on subsidiarity (are there alternatives?), proportionality (are the means and ends in proportion?) and necessity.

Step 6 — **Decision making and justification** (page 72)

Decide on the steps to be taken and justification.

Step 7 — **Feedback and evaluation** (page 72)

Set up processes to follow developments in a targeted manner and periodically evaluate the decision.
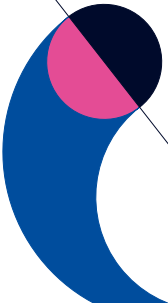
Figuur 01   EQTA – Quick Scan and roadmap

EQTA IN A NUTSHELL

The complete EQTA roadmap consists of the **EQTA Quick Scan**, an **exploratory part** (step 1, 2 and 3) and a **practical part** (step 4, 5, 6 and 7).

General note in advance:
The steps address the same issues from different perspectives and interests. As a result, the outcomes of the steps are often related, and some overlap is inevitable. Try to avoid duplication and do justice to the different perspectives and interests.

Some questions from the step-by-step plan may not be answered properly yet, for example because the idea about the application is still very global at a certain point in time. It is important to set up processes so that relevant developments can be addressed in a timely manner.

EQTA-Quickscan

The Quick Scan aims to quickly create a picture of what quantum technology brings to organizations and what opportunities the technology offers. Depending on the findings, the EQTA ends after the Quick Scan.

The Quick Scan consists of the following parts:

- Exploration of quantum technology. A brief orientation to quantum technology and timelines.
- Exploration of applications: what is in store for your organization? what will quantum technology mean for your organization if the technology is applied, or if you apply quantum technology yourself?
- In a stakeholder analysis, explore who (broadly speaking) will be affected by these applications in and around your organization
- Organize a dialogue between stakeholders, organizations, and experts. The aim of the dialogue is to get the most realistic picture possible of the impact of quantum technology, the opportunities for the organization and the preconditions for exploiting these opportunities responsibly.

If the Quick Scan shows that the organization needs to act now or start actively monitoring developments, proceed to Step 1 (Exploration).

Exploration

Step 1 : Explore the societal framework

- Perception: explore which groups need to contribute to the application and what they need to know about quantum technology.
- Socio-technical ecosystem: explore the social and technical conditions for successful application of quantum technology. Consider: skills and knowledge, organizational processes and governance, and the significance of the application to the technology the organization uses.
- Stakeholders: explore who the application will affect and how to engage these groups.
- External dependencies: explore whether adjustments are needed to the rules and procedures governing the application domain, (professional) codes and best practices, or standards. Explore whether cooperation is needed with third parties (business (chain) partners, regulators, political/administrative) to realize this application. (See also step 3 - Legal and ethical frameworks)
- International context: explore in what ways the application depends on international cooperation and geopolitical developments and how these international dependencies can be monitored and influenced.

Step 2 : Explore technological frameworks

Explore the requirements for the application:
- From a technical perspective, focusing on quality aspects such as security, reliability, and sustainability.
- From the technical boundary conditions for security, trust, and data governance. For instance, participation in (and development of) data ecosystems, trusted and secure supply chains for technology and cloud, authentication, and authorization.
- From the perspective of future-proofing investments, freedom of choice and flexibility of the organization to determine the pace and direction of innovation.

Step 3 : Explore legal and ethical frameworks

**Explore the legal frameworks that apply to the application:**
- International: fundamental rights and treaties.
- Domestic, sectoral, or industry specific.
- (government) Oversight in terms of financial, security, continuity, and accountability.
- Intellectual property, technology-specific (think AI Act or restrictions on dissemination/use of technology).
- Geopolitics: frameworks regarding (inter)national sovereignty, restrictions on collaboration with people and companies.

Explore organizational ethical frameworks:
- Map out how quantum technology can contribute to organizational values that are important to the organization.
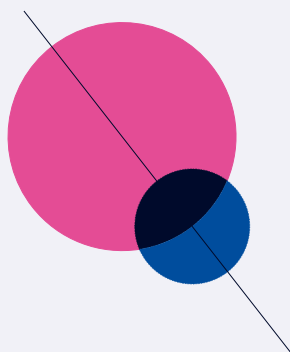
In practice
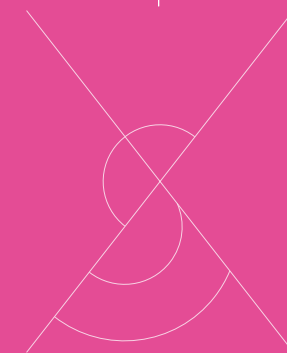
Step 4 : Stakeholder dialogue
(also last step EQTA Quick Scan)

Organize a dialogue between:
- Experts who can create an understanding of the opportunities of quantum technology and have knowledge of the technical, social, ethical, and legal frameworks.
- Administrators who are steering the organization.
- Stakeholders who experience the impact and work with the technology.

The purpose of the dialogue is to describe a tangible approach for the organization including their advantages and disadvantages, based on the perspectives from various groups.

Step 5 : Balancing subsidiarity, proportionality, and necessity

Compare the approaches from Step 4 on subsidiarity (are there other options to achieve the goals?), proportionality (is the impact of the approach proportional to the goal?) and necessity (is the approach necessary to achieve a goal?).

Step 6 : Decision making, recording, and justification

Document the choices made and accountability.

Step 7 : Feedback and periodic evaluation

Design the processes to ensure that applications are realized and that they produce the intended outcomes. Actively manage the delivery of these outcomes.

PREFACE

Quantum technology is promising. It offers unprecedented new opportunities and innovation potential. At the same time, this area of technology is still developing considerably and not all applications have yet come to fruition.

Organizations that are already interested in quantum technology often involve the pioneers in the organization: the technical experts and innovation managers who want to know what is coming their way, or who want to start further developing and using an actual application.

It is precisely at this stage of exploring and investigating the potential of the technology in a particular application area, that expanding the exploration to the broader societal, ethical, legal, and technical context may be necessary to ensure that opportunities are seized, and negative impacts are avoided.[2]

With the aim to provide practical guidance to quantum pioneers in organizations to help them shape the expansion and interpret within organizations how the ethical, legal, and societal aspects may affect the organization, we would like to present the Exploratory Quantum Technology Assessment (EQTA). It offers a concrete roadmap focused on actual applications, provides depth and background on the steps

2   Lessons from AI: stakeholder engagement – Quantum Delta Nederland (2022).
      https://quantumdelta.nl/news/qdnl-white-paper-2-3-lessons-from-ai-communication.

to take, and outlines examples and real-world scenarios. The EQTA helps organizations visualize the potential impact for their sector.

"Quantum technology is promising but is still in its infancy when it comes to applicability."

The EQTA was commissioned by Quantum Delta Nederland (QDNL) and has taken shape in a working group that unites three worlds: the creators of the technology, innovation managers and quantum pioneers at companies and organizations that want to work with it or are affected by it, and lawyers and ethicists. EQTA brings together these very different perspectives in an accessible language.

The working group assumed the following principles to achieve integration: constructive, participatory, bottom-up and practical. You will find reference to the various points of contact at QDNL and the Center for Quantum & Society. In this initiative, all stakeholders are working together in co-creation.

We wish you much inspiration, insight, and success in taking the next step!

Freeke Heijman *(board member QDNL)*
Bart Schermer *(chairman working group EQTA)*
Daniël Frijters *(co-chair working group EQTA)*

The members of the EQTA working group
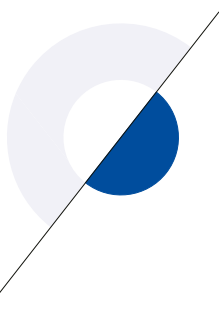
Freeke Heijman

Co-founder Quantum Delta NL, director ecosystem development, she commissioned the creation of the EQTA.

"Because Quantum Technology is still in the phase of research and development, it is difficult to imagine how it will affect society in the near future. For many people, companies, and organizations it is still a long way off. Nevertheless, it is important to prepare today for the societal implications so that we can make the most of the opportunities and mitigate the risks. This requires an active approach to work with end users and civil society organizations to identify the ethical, legal, and societal implications of possible quantum applications. To this end, the QDNL Center for Quantum & Society's Exploratory Quantum Technology Assessment provides a concrete roadmap."

Bart Schermer

Chairman Guidance Group EQTA, Professor of Privacy & Cybercrime, Leiden University and Partner Considerati.

"Quantum technology has a potentially large impact on society. By looking at the ethical, legal, and societal impacts early in the development of this technology, we have the best chance of applying it in the future in a responsible manner."

Daniël Frijters

Co-chair guidance group EQTA, MT member ECP | Platform for the Information Society.

"From the Centre for Quantum and Society at Quantum Delta Netherlands, I am involved in developing insights and tools around responsible innovation. Quantum technology is promising but is still in its infancy when it comes to applicability. For balanced integration in society, it is crucial to start the dialogue today about important themes as well as to offer practical tools for organizations to guide innovation."

THE MEMBERS OF THE EQTA WORKING GROUP

Camille de Valk

Quantum algorithm developer at Capgemini.

"At the Capgemini Quantum Lab, I experiment with partners to bring applications of quantum technology one step closer. I believe we need to look for business processes where now (due to insufficient computing power) many simplifications are made, for example in finance or pharma. Quantum technology brings a new reality where we can calculate the things we would not even dare dream of today."

Eelco Vriezekolk, Lizzy Polman

National Inspectorate for Digital Infrastructure.

"The National Inspectorate for Digital Infrastructure (formerly Radiocommunications Agency) started to investigate quantum technology in 2021 and the impact on society of the diverse applications currently under development, albeit in different timelines. Quantum technology offers many opportunities but can also have undesirable effects if organizations are not prepared in time.

The Exploratory Quantum Technology Assessment helps to accelerate awareness within organizations and provides a step-by-step guide to discuss the societal and organizational context in which the quantum application will take its place. This is how the Netherlands will remain securely connected."

"Quantum technology offers many opportunities but can also have undesirable effects if organizations are not prepared in time."

Frank Phillipson

Senior scientist at TNO and professor of Computational Operations Research at Maastricht University. Frank specializes in optimizing telecommunications, energy, and logistics networks. His research focuses on new techniques for optimization and Machine Learning with quantum computing.

"TNO is committed to technological developments for societal and economic challenges. Compliance with legislation — such as privacy — and ethics is crucial."

Jelle Attema

Advisor ECP | Platform for the Information Society. Secretary EQTA guidance group.

"The development of the EQTA has been an exciting journey. I hope the EQTA is going to help organizations recreate what I believe the working group succeeded in doing: bringing various areas of expertise and perspectives into fruitful and creative conversation with the goal of being able to responsibly capture the wonderful opportunities of quantum technology."

Germain van der Velden, Loulou Hanna, Sterre Romkema
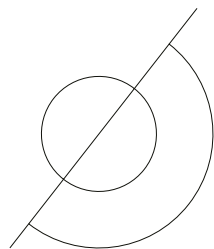
Ministry of Infrastructure and Water Management.

"The Ministry of Infrastructure and Water Management (IenW) works towards a livable, accessible and safe Netherlands. By having early insight into the opportunities and threats of new technologies such as quantum technology, IenW can properly anticipate these technologies. For quantum technology, it means that for now we focus on limiting the future threats posed by quantum technology. By doing so, we will continue to keep the Netherlands livable, accessible, and safe in the future."

ing. Oscar Covers RE MSc

Cyber Security Analyst at the Dutch Banking Association (NVB).

"I am a Cyber Security Analyst and quantum enthusiast. In my role, I analyze ICT-related security risks for the financial sector and — where necessary — coordinate the response."

Jacqueline Schardijn

Senior Business Developer, InnovationQuarter Zuid-Holland.

"We must take action to develop and apply quantum technology in our province so that industry and residents can benefit from it. This is also how we can take a leading role, both nationally and in Europe."

Eline de Jong

PhD candidate Philosophy and Ethics of Quantum-Safe Cryptography and co-author of the WRR report 'Mission AI. The new system technology'.

"In the report 'Mission AI', the WRR shows the ways in which a system technology like AI is embedded in society. These insights are also relevant to our ambitions with quantum technology. With an exploration of the social context, the EQTA broadens our view of the factors that contribute to the successful application of this new technology in practice."

Harry van Geijn

Digital Advisor at Microsoft Netherlands.

"As Digital Advisor, I have been supporting Microsoft's major customers on the business and ethical aspects of technology for over ten years. The focus is on the innovative application of IT, the organizational design of the information function and the impact of technology in terms of ethics and sustainability. In addition, as a (self-proclaimed) nerd, I read books on nuclear physics as a child. So, getting interested in quantum technology at an early stage was inevitable. Being allowed to contribute to the EQTA has therefore been a nice outcome."

Pieter Vermaas

Researcher in philosophy of technology, TU Delft

"I work as a philosopher of technology at TU Delft on the ethical and societal impact of quantum technology and lead ethical research for the Centre for Quantum and Society at Quantum Delta Netherlands. The major challenges I take up are being able to assess the future applications of quantum technology realistically and giving stakeholders the ability to understand and assess those applications."

Mark Wiertsema

Digital Advisor Microsoft Netherlands.

"Together with Harry van Geijn, I am one of the founders of the Quantum Team at Microsoft Netherlands. Personally, I am fascinated by the promise and dynamics of the technology. Its extraordinary properties allow us to do extraordinary things with it. As Microsoft works to make quantum (computing) technology available, we feel responsibility to do so in a safe and responsible way. The NL Quantum Team has therefore set itself the goal of helping society, organizations and individuals to be ready for the adoption of this new technology. Participating in the EQTA is a wonderful way to do this and I hope that the project will contribute to securely fulfilling the promises of quantum."

Marianne Schoenmakers

Senior Consultant Responsible Tech at Considerati, co-author of the EQTA.

"Together with the Responsible Tech team at Considerati, I advise companies and organizations on social and ethical aspects of the deployment of (new) technology and data. Quantum technology, compared to AI for example, is still at an early stage of development. That offers the unique opportunity to include social and ethical aspects in the design phase of applications. I see it as a kind of ethics by design."

Mauritz Kop

TTLF Fellow and Visiting 'Quantum & Law' Scholar at Stanford Law School, Stanford University, USA, and Director of AIRecht.nl, Netherlands.

"It was inspiring to work in a multidisciplinary setting on the world's first assessment tool for quantum technology. From a quantum ELSPI (ethical, legal, societal, political) perspective, I co-wrote the societal, legal, and ethical frameworks of the EQTA with a focus on intellectual property, regulation and social embedding. Instituting a risk-based legal-ethical framework combined with standardization, certification, and technology impact assessment over the life cycle of quantum-driven systems such as computers, sensors and communication networks is crucial to ensure responsible quantum innovation. Thanks to ECP and QDNL for bringing together all the collaborating parties!"

Remco Helwerda

Visionary Advisor, KPN.

"KPN's mission statement is: 'We are committed to connecting everyone in the Netherlands to a sustainable future.' That is why it is important that we watch technological developments that can contribute to that sustainable future, such as quantum technology. The EQTA has become a great tool for that."
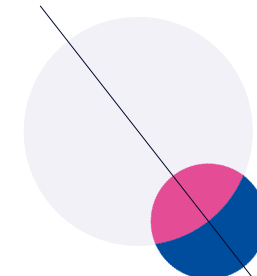
Table of contents

01

The relationship between EQTA, Quantum Delta Nederland and other assessments   29

02

The EQTA roadmap   35

03

Quantum technology examples   75

APPENDIX 01

### Quantum technology in brief   89

01
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THE RELATIONSHIP BETWEEN EQTA, QUANTUM DELTA NEDERLAND AND OTHER ASSESSMENTS

This chapter considers how the EQTA relates to other assessments that many organizations may be familiar with, for instance, the Data Protection Impact Assessment (DPIA).

The EQTA and Quantum Delta Netherlands (QDNL) are also related. After all, the EQTA is limited in scope and, when going through it, readers will undoubtedly have questions. The section on Quantum Delta Netherlands addresses the various ways QDNL can help readers answer their questions.
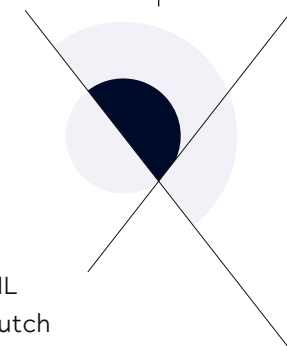
HOW DOES THE EQTA RELATE TO OTHER ASSESSMENTS?

Many tools and methods exist to assess the negative impacts of new technologies and services. Consider, for example, the Data Protection Impact Assessment (DPIA) or the Human Rights and Algorithms Impact Assessment (IAMA).

The EQTA is not a substitute for other assessments, such as the DPIA or IAMA, that may be conducted in addition to or complementary to this tool. For example, when quantum technology is used to develop better Machine Learning models, it makes sense to use the IAMA in addition to this tool, which specifically looks at the negative effects of algorithms.

Essentially, the most important added value of this tool lies in providing an early and structured approach to the consideration of the impact of quantum technologies

EQTA AND QUANTUM DELTA NEDERLAND

The EQTA was written on behalf of Quantum Delta Netherlands (QDNL) and specifically commissioned by the Centre for Quantum and Society (CQS). The center is dedicated to ELSA tooling & research (ELSA is an abbreviation of Ethical, Legal and Societal Aspects), awareness creation and the societal issues to which quantum technology can contribute.

Going through the EQTA will often raise questions from organizations about many aspects of quantum that the EQTA does not address. The CQS is the first port of call to ask these questions and ask for help.

SUMMARY OF QDNL'S ACTIVITIES

CQS is part of Quantum Delta Netherlands (QDNL). QDNL coordinates efforts around quantum technology in the Dutch ecosystem. The following issues are being addressed:

Quantum Awareness (on a societal level)

Quantum.Amsterdam (https://www.quantum.amsterdam/, or specifically: https://www.quantum.amsterdam/education/workshops-and-training/) offers awareness training from the Quantum.Amsterdam hub as a networking organization to understand the technical, economic and societal impact of quantum technology, with a focus on computing.

Quantum for Business (https://www.quantumforbusiness.eu/) is a field lab within the QDNL program and targets the European market of companies and organizations and aims to facilitate access to knowledge about quantum technology and the parties to collaborate with.

Co-creation sites

Centre for Quantum & Society (https://quantumdelta.nl/cqs/) is the central co-creation activity from the QDNL Quantum & Society program. A virtual and physical place where parties from society, industry, government, and science come together to work on the application of quantum technology for the benefit of society.

House of Quantum (https://www.houseofquantum.com). This is to become an organization of national physical spaces within the QDNL ecosystem where members can work, learn, and come together.

De DELTA Hub (https://quantumdelta.nl/our-hubs/). The QDNL program has 5 hubs (Delta, Eindhoven, Leiden, Twente, and Amsterdam) where all kinds of co-creation activities take place.

Application development and societal impact

Het Quantum Applicatie Lab (https://quantumapplicationlab.com/). A field lab within the QDNL program, where various parties and quantum tech providers are working to develop useful quantum computing applications for end users. This may involve societal issues, working in collaboration with the CQS.
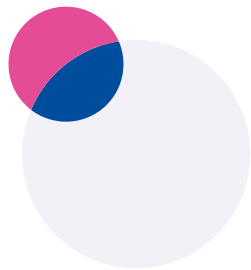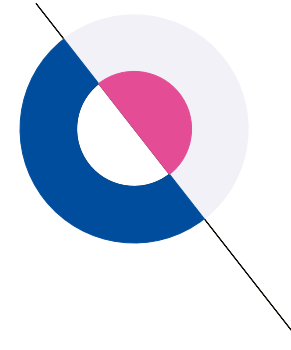
02

THE EQTA ROADMAP

QUICKSCAN

The Quick Scan is described in the section 'EQTA in nutshell' ().
The Quick Scan develops an initial picture of what quantum technology
will mean for an organization, the opportunities that quantum
technology offers an organization, and the possible negative effects.

The Quick Scan then broadly explores what is needed to achieve
responsible application and manage negative impacts, by weighing
the various interests (of the organization itself and of other
stakeholders) and identifying the technical, social, legal, and
ethical boundary conditions.

If the Quick Scan shows that an in-depth analysis is required, the
step-by-step plan described in this chapter is implemented.

EXPLORATION

Step 1: Social framework

The deployment of quantum technology always takes place within a larger setting: society. A quantum application must not only function technologically, but it must also above all function in society. Here we are dealing with issues that are not (entirely) within the sphere of influence of individual organizations. Consider legislation, infrastructure, and public opinion. So, if we want to explore what it will take to make quantum technology work, it is important to be aware of those factors as well. In the first step of the EQTA, we therefore consider the social context of quantum applications.

By analyzing the social context, we expand our view of the role of individual organizations. We show which broader processes affect the application of quantum technology. In addition to choices about their own application, organizations can also help shape those processes. Furthermore, we show that individual organizations are not the only players determining how quantum technology finds its way into practice. Organizations are partly dependent on other actors in this regard.

System technology
To gain insight into the social context in which organizations engage with quantum technology, we draw upon the Scientific Council for Government Policy (WRR) report on the task of Artificial Intelligence (AI).[3] In this report, the WRR analyzes the embedding of Artificial Intelligence (AI) in society.

AI, like quantum technology, can be regarded as, what the WRR calls in the study a system technology:[4] a technology that enables a great deal of innovation, in all kinds of fields, and therefore has a 'systemic' impact on society. Examples are electricity, the internal combustion engine, and the Internet. Based on our experiences with previous system technologies, the WRR draws several lessons on how to approach new system technologies, such as AI. We can also learn from the past in the case of quantum technology.
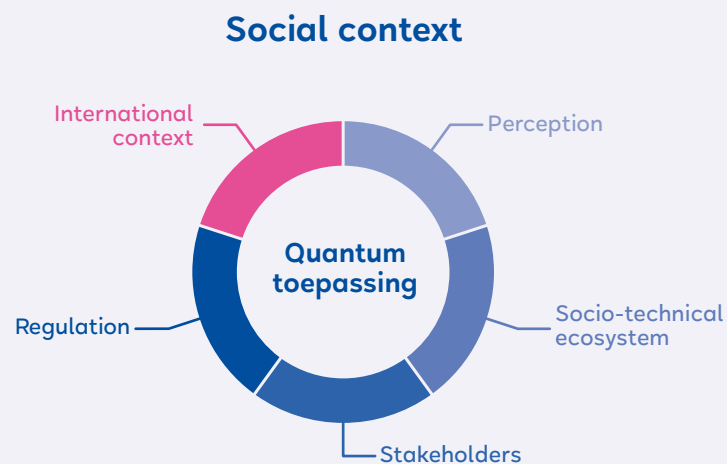
Incidentally, some working group members have issues with categorizing AI and quantum technology as systems technology. The risk of the label 'systems technology' is that there seems to be a discontinuity: the notion that attention to the impact of a technology and the need to analyze it is only needed now. Whereas those impacts often occur even when previous technology was applied. Emphasizing the discontinuity can lead to technology-specific regulations that will regulate problems with new technology but will not regulate the same problems with existing technology. The attention the EQTA advocates for social and ethical aspects of quantum technology is therefore a plea for a critical analysis of existing applications of information technology as well.

If we want to embed a new systems technology in society in a responsible and successful way, the WRR points out that five things are important:
- Countering unrealistic perceptions (demystification);
- Creating a favorable socio-technical ecosystem contextualization);
- Involving stakeholders (engagement);
- Establishing regulatory and guiding frameworks (regulation);
- Monitoring international relations (positioning).

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3   https://www.wrr.nl/publicaties/rapporten/2021/11/11/opgave-ai-de-nieuwe-systeemtechnologie.
     English summary: https://english.wrr.nl/publications/reports/2021/11/11/summary-mission-ai.

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4   The WRR focuses on so-called 'system technologies': technologies with a broad and profound — in short, systemic — impact on society. Examples of such system technologies are electricity, the internal combustion engine, and the computer. From our experiences with previous system technologies, the WRR draws several lessons for our dealings with new system technologies, such as artificial intelligence (AI). We can also learn from the past in the case of quantum technology.

Social context

Quantum toepassing

- International context
- Perception
- Regulation
- Socio-technical ecosystem
- Stakeholders

Figure 01 Five aspects of the social context of quantum applications

We can see these social tasks as five aspects of the social context of quantum applications (see Figure 01). It is important for organizations that want to put quantum technology into practice have insight into this context, because the success of an application is partly determined by it.

Using the following questions, they can identify the social context:
- What are the perceptions surrounding quantum technology?
- What are the social and technical conditions for success?
- Who is impacted by the application?
- What are the applicable frameworks?
- What is the international context?

On the next pages we explain these questions in more detail and look at how organizations can work with them themselves to shape the social context for each task.
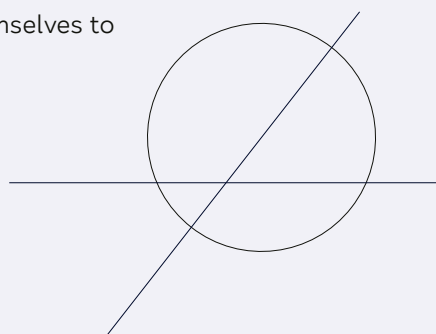
What are the perceptions surrounding quantum technology?
Demystification is about the perception surrounding a technology. Oftentimes, many ideas develop about how a new system technology works and what that technology is capable of. However, these ideas do not always match reality. This may cause problems in the application of the technology in practice. 'Excessive expectations lead to disillusionment and ill-considered applications, while exaggerated fears lead to aversion to the technology and failure to take advantage of the opportunities it offers', write the compilers of the WRR report.

Thus, if we want people to be open to a new technology and able to think about the opportunities and negative effects of applications, it is necessary to demystify the technology. Which means getting rid of the myths surrounding it and favoring a realistic view of what the technology can and cannot do.

Complex and promising
The combination of complexity and great promise makes quantum technology susceptible to mythmaking. One example of quantum technology that easily becomes the subject of mythmaking is the quantum computer. The idea exists at times that a quantum computer would be superior to a classical computer in all aspects. This is unfair: quantum computers promise an advantage for a certain type of problems. In addition, quantum technology is still unknown to many people and to some extent will remain incomprehensible for a very long time - even for experts. This may translate into a lack of interest and a failure to debate the opportunities and negative effects in society. At the same time, not everyone needs to know exactly how quantum technology works. What matters is that its application is not hindered by unrealistic perceptions and that people are able to participate when thinking about its applications.
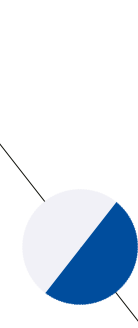
For organizations that want to apply quantum technology themselves, it is therefore useful to first examine what perceptions exist and how these may affect the intended application. It is also important to be alert to one's own (unintentional) contribution to perception, for example by using certain words. Next, it is important to think about the question of who needs to know what: which groups of people should be able to think about the intended application and thus have sufficient knowledge? Depending on the answer, organizations can work internally on the required knowledge, or more broadly within society along with other actors on comprehension.

Question 1

PERCEPTION

What is the perception surrounding quantum technology?

Auxiliary Questions:
- What ideas exist inside and outside the organization about quantum technology and how might that affect the intended application?
- Which groups or individuals should be able to participate in the application? What do they need to know?

What are the social and technical conditions for success?
Contextualization focuses on creating a favorable socio-technical ecosystem. That is, an environment in which both social and technical factors promote the functioning of any technology. For example, it is necessary that the people who will work with the technology are well-equipped to do so and that the processes within an organization match the new application (the social conditions).

In addition, the presence of supporting technologies and a good infrastructure is crucial (the technical conditions). The WRR therefore emphasizes that if we want a technology to really work in practice,

we must not only look at the performance of the technology itself, but also at the environmental factors that support the performance. As an example, the WRR uses the self-driving car: it only functions properly in practice if the occupants in the car and the cars of fellow road users can also use it properly and if the environment becomes more 'readable' for the car through smart signage.

Conditions socio-technical ecosystem
These types of social and technical factors are also crucial when discussing the social context of quantum technology. For quantum technology to work in practice, supportive hardware and software are needed. For example, quantum computers involve the availability of quantum chips, appropriate programming languages and the development of quantum algorithms for solving certain problems. Experts[5] expect quantum computing power and simulators of quantum computers to become available primarily as a cloud service. For example, Quantum-Inspire from Qu-Tech Delft offers quantum computers as-a-service (see https://www.quantum-inspire.com/).

In that case, success in practice will depend in part on access to those cloud services. Creating such conditions is by no means always within the reach of individual organizations, but they can call others to account or offer support.

When applying quantum technology, it is therefore important to examine what the social and technical conditions are for success in practice. In doing so, organizations should first ask themselves what the quantum application requires of the social environment: What must the people who work with it be able to do? Are adjustments needed in the way of working within the organization?

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5   Hoofnagle, C., & Garfinkel, S. (2022). *Law and policy for the quantum age.* Cambridge University Press.

In addition, the technical environment must be checked: What kind of technical ecosystem does the application assume? How can adjustments to the environment improve the functioning of the application?

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Question 2

SOCIO-TECHNICAL ECOSYSTEM

What are the socio-technical conditions for success?

Auxiliary questions:
- What must the people working with the technology be able to do (skills) and are adjustments needed in the way they work within the organization?
- What kind of technical ecosystem does the application presume and how can adaptations to the environment improve its functioning?

</div>

Who will be impacted by the application?
Engagement is about involving stakeholders during the development of a technology and in implementing and gathering feedback on that technology. For a technology to be responsibly and sustainably embedded in society, the WRR argues, it is crucial to 'democratize' the technology, as it were. This means giving different groups a voice in the design and evaluation of a technology. As it often happens, technology development is dominated by technical considerations and developer interests.

Involving stakeholders in the development, implementation and evaluation of a technology not only allows better anticipation of possible (undesirable) effects, but also increases public support.[6]

Different perspectives
Stakeholders are part of the social context of quantum technology. The specialist nature of the technology and the associated high costs carry the risk that the development of quantum technology will belong to a small group of specialists.

If we want to make full use of the potential of quantum technology and prevent undesirable effects as much as possible, it is important that different groups can contribute ideas about the opportunities and negative effects of quantum technology. This can be done, for example, by gathering different perspectives and interests during the development, implementation, and evaluation of a quantum application.[7]

For organizations that want to imagine the social context in which a quantum application will emerge, it is therefore important to consider which groups will be affected. In what way will they be 'impacted' by the intended application? And how can those groups be involved — in advance and structurally — so that there is insight into the impacts of a quantum application?

6   See for a detailed source on proactively anticipating the social aspect of quantum: E. De Jong, *Own the Unknown: An Anticipatory Approach to Prepare Society for the Quantum Age, Digital* Society, Quantum-ELSPI TC, 1, https://link.springer.com/article/10.1007/s44206-022-00020-4.

7   Making the technology and forms of … accessible is an important part of Quantum Delta Netherlands' mission. For more information: see page 30: *EQTA and Quantum Delta Netherlands.*
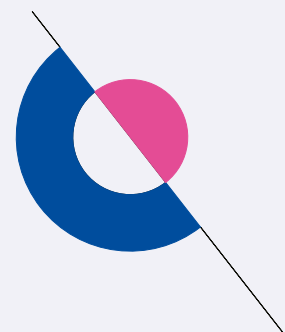
Question 3
STAKEHOLDERS

Who will be impacted by the application?

Auxiliary questions:
- Who will be 'impacted' by the intended application, and how?
- How can these groups be involved in development, implementation, and evaluation?

What regulatory frameworks apply?
Regulation refers to all the regulatory and guiding frameworks that define the space within which a technology can be developed and applied. New technologies do not usually emerge in a vacuum. A variety of frameworks often already exist and can be applied (after modification). Sometimes, however, a technology creates unprecedented circumstances and new rules are called for. At that point, we often do not know exactly what kind of rules are needed because we have little experience with the technology. In that case, according to the WRR, flexible instruments such as standards and norms offer a solution. Regulation is thus a balancing act between creating space and establishing rules that frame, and direct, the development and application of a technology.

Rules of the game
Regulatory frameworks form the fourth aspect of the social context that governs the application of quantum technology.
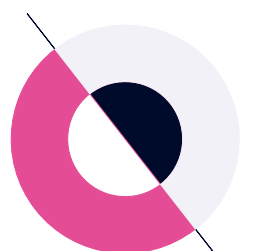
How quantum technology relates to existing legal frameworks is discussed in Step 3: *Legal and ethical framework*, like those governing intellectual property.[8] In addition, work is underway to develop standards, such as those for post-quantum cryptography and cybersecurity. Both present and newly developing frameworks are part of the societal context. After all, how quantum technology can be applied in practice depends partly on the prevailing rules of the game.

It is therefore important to consider how an intended application relates to existing frameworks. What regulations apply? The answer to that question may also be that adequate regulations are currently lacking, which could jeopardize issues such as legal certainty, and lead to abuses. Some of the frameworks that organizations encounter when applying technology are professional: lawyers, accountants, doctors, civil servants, or notaries are sometimes required to take on certain responsibilities that may conflict with the application of technology, or which could be performed much better with the help of technology.[9]

New agreements and sometimes new institutions are needed to make some applications possible. Take, for example, setting up systems with new roles, such as that of a system authority aimed at enabling organizations to exchange sensitive data easily and reliably within applicable frameworks. Developing the agreements and setting up such systems requires close cooperation between organizations, regulators, and professional organizations such as auditors. Depending on the type of frameworks needed, organizations can develop those frameworks themselves or put this on the agenda of other professional groups involved in this process.

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8   See for to intellectual property: Aboy, M., Minssen, T. & Kop, M. *Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications*. IIC 53, 853–882 (2022). https://doi.org/10.1007/s40319-022-01209-3.

9   Consider such now-forgotten anachronisms as the requirement of a 'wet' signature on a contract, or the requirement of physical presence of a person to establish identity (preferably with a 'photocopy of one's passport' as proof), while the person possesses a reliable digital proof of identity with which to prove one's identity.

An important theme that recurs in Step 2 is standardization: in order to be able to switch to other vendors or service providers in the future—without high costs such as reinvestment—it is important that organizations using technology develop high-quality standards in a timely manner together with the providers, which can anticipate future developments and have broad support.

Question 4

REGULATORY

What frameworks apply? (See also step 3)

Auxiliary questions:
- What regulations apply to the intended application?
- Are there gaps that call for new or modified frameworks?

What is the international context?
Positioning is about relationships on the international stage. The WRR shows that the development of a new systems technology is often framed as an international race. However, that frame is simplistic and misleading because it implies that there is one winner. In reality, the WRR argues, one person's gain is not necessarily another person's loss. However, it is important to think strategically about one's own international position in relation to other actors, especially when it comes to competitiveness and security issues regarding a technology.

Although perception, the socio-technical ecosystem, stakeholders, and regulations all have an international dimension, the international context is also an aspect that stands alone and deserves attention. Due to its specialized nature, the research community of quantum technology is highly intertwined internationally: experts from all kinds of countries join forces to achieve breakthroughs. Moreover, the development of quantum technology is very costly, which is why only a small number of players currently play a dominant role in the field worldwide. For these reasons alone, the application of quantum technology almost always has an international component.

The international playing field: sovereignty
For the analysis of the social context, it is therefore not only important to have an eye for the international dimension of the aspects discussed earlier, but also to explicitly consider the international playing field in which an organization operates. That dimension is increasingly dominated by sovereignty: the geopolitical (technological) self-determination of (groups of) countries, such as the Netherlands, the EU, et cetera. From that desire for self-determination may follow export and import restrictions, geopolitical restrictions on working with people and organizations from some countries outside Europe, and restrictions on foreign interests in company ownership.

The focus and desire for sovereignty is sometimes at odds with the international interconnectedness of the research community.

Questions that arise in this context are: what players are involved in the intended application and what dependencies may arise? Do foreign actors have access to the application, what are possible implications?
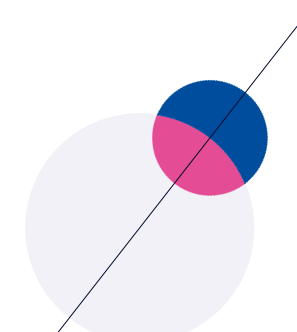
Question 5
INTERNATIONAL CONTEXT

What is the international context?

Auxiliary questions:
- What international actors are involved in the intended application? What dependencies may arise?
- Do foreign actors have access to the application? What are possible implications?

Step 2: Technological framework

To identify the impact of a technology application on people and society, it is important to describe the more generic requirements of the technology. Quantum technology is becoming part of applications where data play a central role. This means that there are generic requirements for the functionality, reliability, and quality of the technology. There are requirements for interoperability with other technology, for how the technology handles data (identity, authentication and authorization, and control over data), and for how the values surrounding that handling of data are interpreted (e.g., preventing monopoly control over data).

Question 6
QUALITY REQUIREMENTS

What are the quality requirements for the technology to achieve the goals and benefits described?

Think about functionality requirements: What can the technology do? What functions does the technology offer? But also, other requirements such as robustness against errors, the ability to analyze and repair errors, securing systems, flexibility requirements and requirements for manageability and the possibilities for integration with other technology. Sustainability (such as origin and reuse of raw materials and energy consumption) also plays a role. Check ISO 25010 for inspiration to establish a complete list of requirements.[10] These quality issues are usually addressed by requiring certifications from the vendor.

Question 7
TECHNICAL REQUIREMENTS

What technical requirements should be imposed in relation to privacy, security, data, identity, authentication, and authorization?

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10   These are examples of requirements taken from ISO 25010, a common framework for identifying and describing the (requirements for) quality of software and systems. For more information: https://nl.wikipedia.org/wiki/ISO_25010.

"Quantum technology is becoming part of applications where data play a central role. This means that there are generic requirements for the functionality, reliability, and quality of the technology."

When addressing these issues, the following questions arise:

- What (technical) principles should be applied to protect privacy and provide data subjects with appropriate opportunities for consent and control?
- What authentication and authorization mechanisms are needed to give the many data subjects control over the collection and use of data?
- How will the reliability and security of data be ensured?
- After all, the powerful computing power of quantum computing will require a lot of data, with parties having to make data available to each other. Choices will have to be made about which data fall into the cooperative purview and which into the competitive one, and which data will be confidential, and which will be open. Joining or developing management organizations that play a role in ensuring the security, privacy and quality of data may be necessary.
- How can the risks of increasing interconnectedness and dependence on third parties in the application of quantum technology be managed?

Note: important parts of these generic requirements for technology and how technology handles data, security and privacy will be regulated by European legislation in the coming years. As such, there is a strong relationship to Step 3: the legal frameworks. Consider the Cybersecurity Act, the Data Governance Act, the AI Act, and the General Data Protection Regulation. Implementing these laws often requires collaboration and fundamental technical choices.

Examples of technical prerequisites for privacy, security, and reliability

Data

Data is needed to exploit the opportunities of quantum technology. In Europe, work is underway on generic principles and architectures aimed at collaborating on data such as: IDS (International Dataspaces)[11], Cathena-X[12] and Gaia-X[13]. The Netherlands hosts two successful examples of these efforts: SCSN (the Smart Connected Supply Network) which facilitates (confidential) information exchange in the large global ecosystem around Brainport, Eindhoven,[14] and Ishare[15] which for many years facilitates intensive data exchange in the logistics sector.

The Ministry of Infrastructure and Water Management is working with parties on an ecosystem around mobility data[16] based on these principles. Similar initiatives exist in the fields of agriculture, healthcare, and energy.

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11 https://internationaldataspaces.org/

12 https://catena-x.net/en/

13 https://gaia-x.eu/

14 https://smart-connected.nl/nl

15 https://ishare.eu/nl/

16 https://www.rijksoverheid.nl/onderwerpen/mobiliteit-nu-en-in-de-toekomst/mobility-as-a-service-maas

Identity

Other areas surrounding the application of quantum technology, such as identity solutions that allow the responsible handling of personal data, are in the pipeline. Think of the upcoming European e-wallet and the principles of Self Sovereign Identity.[17]

Information security and continuity

Quantum technology is often acquired as a service. These services will run on software that is constantly being developed and improved, by numerous parties. Also, data will be collected and shared by many parties. The result is increasing technical interconnectedness and interdependence of different parties. This requires targeted action to manage risks around information security and continuity. The financial sector is (understandably) leading the way here, with parties systematically exchanging information about risks, measures, and their effectiveness based on the International Standards for Assurance Engagements (ISAE). In the Netherlands, parties work together in the Online Trust Coalition with the aim of applying these principles to manage risks around information security and continuity in complex networks.[18]

Interoperability of data

Finally, on the subtopic of data interoperability, work is being done on the FAIR (Findable, Accessible, Interoperable, Reusable) principles. The ability to automatically understand and combine data from so many different sources, as well as effective possibilities for control, requires standardization of data interoperability.

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17 https://www.rvig.nl/self-sovereign-identity

18 https://onlinetrustcoalitie.nl/en/
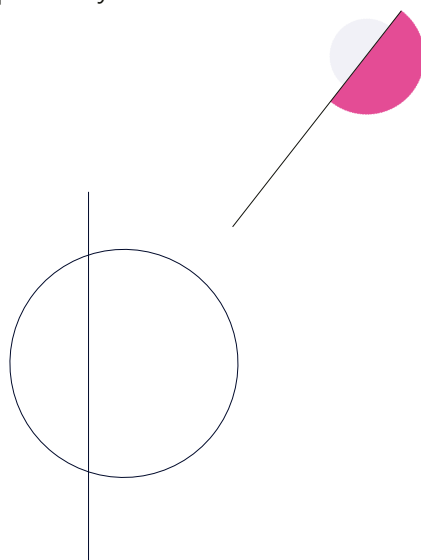
Question 8

FUTURE PROOF INVESTMENTS

Which preconditions should be set on quantum technology to ensure future proof investments and freedom of choice for organizations in future?

Future-proofing investments and freedom of choice for the organization in future?

With new technology, there is always a phase when some parties dominate the market because they are the first to bring an application to market. An important question an organization must consider at this point: When do you jump in? An important consideration may be the future-proofing of investments and the likelihood of vendor lock-in and thus the freedom that the organization can continue to make its own technical choices in the future. After all, many new technologies employ 'proprietary' standards, owned by a specific technology developer, which makes it difficult to move to or integrate technology from other vendors.

Technology users should therefore seek cooperation with other users and vendors at an early stage to achieve open standards for quantum applications. NEN, Royal Netherlands Standardization Institute,[19] is involved in many of these international standardization processes. NEN can take the initiative for new processes (under certain conditions) and can play a role in establishing contacts with standardization committees.

Technology suppliers often cooperate in standardization to ensure that the standard allows for future developments and fits their strategic approach. Also, the very existence of standards gives confidence to customers that a solution is mature. Confidence leads

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19 https://www.nen.nl/en/

to demand and is therefore good for technology development. In addition, the existence of standards gives innovators the opportunity to quickly enter an existing market.

## Step 3: Legal and ethical framework

Legal framework

For the deployment of quantum technology, the legal frameworks within which an application operates must also be considered. Legal and ethical frameworks go hand in hand.[20] Legislation is sometimes 'solidified ethics', when norms, values and ethical principles are transformed into laws and (behavioral) rules. The legal framework then provides a context for making ethical considerations.

However, ethical considerations can also exist in their own right, regardless of whether legal frameworks will ever emerge. For instance, choices around sustainability or employee benefits. An organization can choose to commit to specific ethical goals, even if they have no legal basis, and be held accountable for them. Many organizations take the SDG (Sustainable Development Goals) as a guide for their ethical choices and account for plans and progress in this area in their annual report.

Making ethical trade-offs is also necessary when legislation is inadequate. With new technologies, legislation either lags behind, or existing legislation needs to be re-examined.

Ethically aligned design
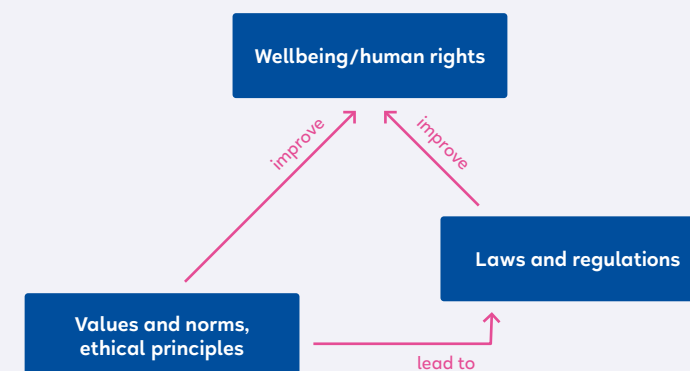
Figure 02 The relationship between values and norms, laws and regulations and wellbeing/human rights (IEEE, 2017) [21]

Legal frameworks set constraints. When considering the use of technology, there are always laws and regulations that must be followed. Legal frameworks restrict the room for maneuver. It is therefore relevant to consider legal frameworks explicitly in addition to ethical frameworks. We distinguish general laws and regulations that can apply to all sectors and application areas. In addition, there is technology-specific legislation to consider. Finally, there is legislation that is sector specific. The overview provided here is long, but not exhaustive. It provides initial direction in identifying relevant laws and regulations.

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20   See for example: M. Kop, *Establishing a Legal-Ethical Framework for QT,* Yale J.L. & Tech. The Record (2021). https://yjolt.org/blog/establishing-legal-ethical-framework-quantum-technology.

21   https://ethicsinaction.ieee.org/ Source figure: https://ethicsinaction.ieee.org/wp-content/uploads/ead1e.pdf.

General legal frameworks involve laws and regulations that apply regardless of application or sector. Examples include human rights, fundamental freedoms and economic or social rights, civil law, criminal law, administrative law, or tax law. We list some of them here.

Human rights
The terms basic rights, fundamental rights or human rights are often used interchangeably. They are legal norms whose purpose is to assure citizens of personal freedoms and a dignified existence. They are rights that apply to all people, regardless of a citizen's nationality. There are several national and international sources for this category of rights, such as:

- International Covenant on Civil and Political Rights (ICCPR);
- European Convention on Human Rights (ECHR);
- Charter of Fundamental Rights EU;
- International Covenant on Economic, Social and Cultural Rights (IVESC);
- The constitution.

General data protection regulation (GDPR)
The AVG is the Dutch implementation of the European General Data Protection Regulation (GDPR). The AVG contains specific rules for the processing of personal data by companies and the government. Among other things, the implementation of the AVG has strengthened and expanded privacy rights. Organizations have also been given more responsibility in this area. In addition, there is a separate directive for data protection in police and justice. These are the Police Data Act (Wpg) and the Judicial and Criminal Records Act (Wjsg).

General administrative law and general principles of good governance
Public bodies must comply with rules of conduct regarding citizens and businesses. Some of these rules are contained in the General Administrative Law Act (Dutch: Awb), but there is also so-called 'unwritten law'. This unwritten law is called the General Principles of Proper Administration (Dutch: Abbb).

Intellectual property and patents
Recent technological developments and geopolitical tensions lead to close scrutiny of the topic of intellectual property and patents. For analysis of the topic in the context of quantum technology, see this footnote.[22]

Specific legislation for quantum technology
Currently, there is no legislation (yet) specifically regulating the social opportunities and prevention of negative impacts of the deployment of quantum technology. It is important here to determine whether the quantum application stands alone or is used in combination with or for the benefit of other technologies, such as artificial intelligence (AI) or biotechnology, for example.

There are already specific rules around the use of AI and data, as described for example in the AVG. Also, in Brussels, the European Union is currently working on the European AI Act. The proposed law divides AI systems, products, and services into four risk categories. The first category is prohibited applications, such as government-run social scoring systems. The second risk category names high-risk applications, such as HR systems. These types of systems are subject to specific legal requirements.

Furthermore, there are two remaining groups of applications that are not explicitly categorized as 'prohibited' or 'high risk', namely *Limited Risk*, and *Minimal Risk*. As the risk of the AI application increases,

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22   Aboy, M., Minssen, T. & Kop, M. *Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications.* IIC 53, 853–882 (2022). https://link.springer.com/article/10.1007/s40319-022-01209-3.

regulatory requirements become more stringent, or prohibited.[23] An important tool to ensure regulatory compliance of high-risk systems is CE marking. This certification is required prior to the market introduction of AI applications.

The EU and US
Whereas Brussels has taken the lead in regulating AI within Europe, Washington adopted quantum-specific regulation for the United States in May 2021 in the form of two Directives.[24] Also, in May this year, a 'national security memorandum' was issued by the Biden Administration. In so doing, on the one hand, the U.S. wants to better facilitate its own market leadership around quantum technology by encouraging innovation. On the other hand, it wants to prevent the technology from falling into the wrong hands and thereby threatening economic stability and national security.

As part of the National Security Memorandum, export controls will be established for certain quantum technologies. It also aims to prevent intellectual property theft ('IP theft') and address and reduce risks about cybercrime.

The AI Act's risk-based approach is well suited to regulating quantum technology as most quantum technologies are dual-use applications — meaning that the applications can be used for both civilian and military purposes, for example nuclear applications (medical isotopes versus the atomic bomb). In addition, the unique properties of quantum require a tailor-made approach. It is therefore expected that the European Union will propose legislation specific to quantum technology within a few years, in the form of a Quantum Governance Act.[25]

It is also conceivable that there will be an international treaty in the form of a Quantum Treaty. It is expected that standardization, certification, and lifecycle auditing by means of binding Exploratory Quantum Technology Assessments will play an important role in this. In addition, because of the current geopolitical situation, it is quite possible that the EU will also issue export controls. This will directly affect research and trade in quantum technology and materials and the fragile supply chain of software and hardware structures. Finally, it is expected that there will be tough requirements for funding quantum R&D.

Proactive anticipation
What does all this mean for Exploratory Quantum Technology Assessment (EQTA) users? It is important to be aware of the legal, ethical, social, and policy aspects of quantum technology. This is also abbreviated as Quantum-ELSPI (where ELSPI stands for Ethical, Legal, Social and Policy Implications).[26] Thus, the EQTA tool can be used to identify current - and future - legal requirements for the use of quantum technology and thus proactively anticipate them. This applies not only to legal compliance, but also to intellectual property opportunities and responsibilities (rights and obligations).

23   For more information on the EU AI Act: Mauritz Kop, *EU Artificial Intelligence Act: The European Approach to AI, Transatlantic Antitrust and IPR Developments* (2021), https://law.stanford.edu/publications/eu-artificial-intelligence-act-the-european-approach-to-ai/.

24   Fact sheet: *President Biden Announces Two Presidential Directives Advancing QT, White House* (May 4, 2021). https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/fact-sheet-president-biden-announces-two-presidential-directives-advancing-quantumtechnologies/.

25   For a transatlantic perspective: Regulating Quantum Technology, https://law.stanford.edu/projects/regulating-quantum-technology/.

26   Examples of Quantum-ELSPI questions relevant for the use of EQTA can be found here: Quantum ELSPI: *Ethical, Legal, Social and Policy Implications of Quantum Technology,* Digital Society (Springer Nature) 2021, https://link.springer.com/collections/eiebhdhagd.
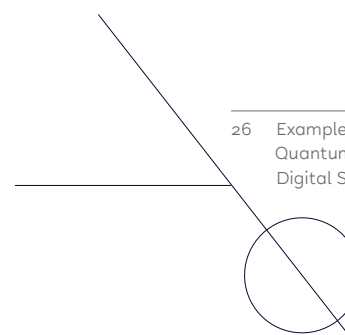
Sector and industry-specific frameworks

Finally, there are specific frameworks for sectors that are important to consider, for example:

- Legislation in the financial sector, for example the Financial Supervision Act (Dutch:Wft) and the Prevention of Money Laundering and Financing of Terrorism Act (Dutch: Wwft).
- Telecommunications legislation (the Telecommunications Act).
- Legislation for patient rights within healthcare, for example the Medical Treatment Agreement Act (Dutch:WGBO).
- Legislation for medical devices in health care (Medical Device Regulation).

There are also (international) laws and regulations in the field of product safety that may be relevant in the deployment of quantum applications. Examples include the Product Safety Directive and the Machinery Regulation.

**Medical quantum applications**

A recent example that illustrates the diverse legal impact of applying quantum technology is the 'quantum-infused medical device' marketed in Europe. Moreover, this also features AI/Machine Learning and classical data. From a legal point of view, this qualifies as a quantum/AI hybrid. This means that in addition to the general legal frameworks, the various technology-specific frameworks (for AI, data, and quantum) apply. In addition, the vertical, sector-specific frameworks (in this case Healthcare/Healthcare) will apply.
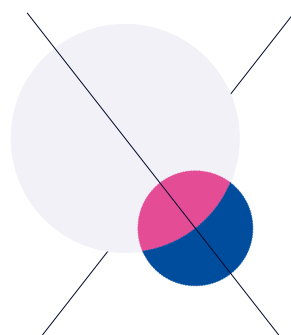
Once the European laws are passed, this means that on these medical devices the following applies (at least):

- The EU AI Act;
- The Quantum Governance Act;
- The range of laws that make up the European Strategy for Data (GDPR, FFD, Data Act, Data Governance Act, etc.);
- The Medical Device Regulation;
- The Database Directive;
- Relevant IP Directives;
- Possibly certain export controls as described in the Wassenaar Arrangement;
- Dutch laws and regulations.

Please note that if you are doing business in the U.S. or Asia, for example, local laws apply there.
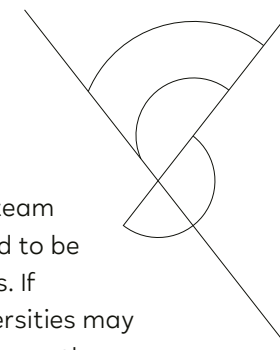
In addition, the EQTA can be used by a multidisciplinary team to look at what intellectual property rights arise and need to be registered, such as patents, copyrights, and trade secrets. If applicable, the technology transfer agreement with universities may be reviewed as well. Optimizing the patent portfolio increases the value of medical devices. Additionally, counterfeiting can be reduced, with help of enforcement. If third-party Intellectual Property is used in medical equipment, the EQTA report will indicate that it must be licensed, to prevent infringement of third-party IP. You can use the EQTA as a guide to identify the above issues, creating more awareness internally and externally about the legal framework.

Complex trade-off: security and privacy

In the context of quantum technology, it is relevant to highlight the complex trade-off between security and privacy. This complexity is particularly relevant in the development of applications in the field of quantum communications and the upcoming quantum internet. The Intelligence and Security Services Act (Dutch:Wiv) and the debates surrounding it, as well as the passing of the Network and Information Systems Security Act (also known as the Cybersecurity Act), Computer Crime III, and the Article 29 Working Group's position on encryption, show that security of the Internet, communications and information is a highly relevant and contested topic. Several interests play a role here. The potential deployment of quantum networks is no different.

On the one hand it is important that sensitive information and communications of both governments and citizens are secure and confidential, on the other hand it is desirable or even necessary for national security — or the investigation and prosecution of criminal offenses in some cases — to be able to intercept certain information and communications.

Appropriate measures

The public debate on the Dutch Wiv, the outcome of the referendum on the Wiv, and the increasing use by citizens of secure VPN connections that use encryption show that people are increasingly concerned with the security and confidentiality of communications. Also, legislation such as the Network and Information Systems Security Act and the General Data Protection Regulation (GDPR) require appropriate measures to be provided to secure networks and data. This could include, for example, encryption.

On the other hand, providers of public telecommunications networks and public telecommunications services only make their networks and services available to users if they are interceptable under Chapter 13 of the Telecommunications Act. A non-hackable form of the Internet thus seems ideal within the framework of one piece of legislation, while it may not be desirable from the perspective of other legislation.

Ethical framework

Ethics is a philosophical discipline concerned with the study of 'doing the right thing'. Ethics does not offer a checklist of what is right and wrong but provides methodologies for arriving at a judgment about what is right and wrong. An important goal of ethical consideration is to ensure that the final quantum application is in line with prevailing societal views of what is ethical. The purpose of this Exploratory Quantum Technology Assessment (EQTA) is not to tell you what is and is not responsible. It is up to the user to assess this. However, the EQTA does provide guidance for arriving at such an assessment.

Digitization and new technologies, such as quantum technology, Artificial Intelligence, and cloud computing, raise ethical questions.[27] They often take the form of a question. For example: Is it acceptable to deploy this technology? Ethical frameworks are related to legal frameworks. Laws and regulations give context to the leeway one has when deploying technology. However, they are not separate from ethics. Social values are translated in society into norms, laws, and rules. Applicable norms and values can thus lead to laws and (behavioral) rules. We treat legal and ethical frameworks separately here because the frameworks have different dynamics for the user. In the legal framework, the law or regulation is the starting point for testing against the desired quantum application. In the ethical framework, societal values are the starting point. You can read more about the legal frameworks in the previous sections. The development of laws and regulations takes time, and is lagging behind the rapid technical developments. As a result, the legal framework often does not yet provide enough guidance and an ethical consideration can be useful.

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27   Information about ECP's Approach and accompanying Guide to Guidance Ethics can be found at https://ecp.nl/publicatie/guidance-ethics-approach/.

The Quantum Computing Governance Principles

The World Economic Forum (WEF) provides a guide for analyzing and framing the translation of ethical concerns in the context of quantum computing into governance: The Quantum Computing Governance Principles (2022).[28] As such, this applies only to quantum computing and not to the entire family of quantum technology.

Quantum computing stakeholders
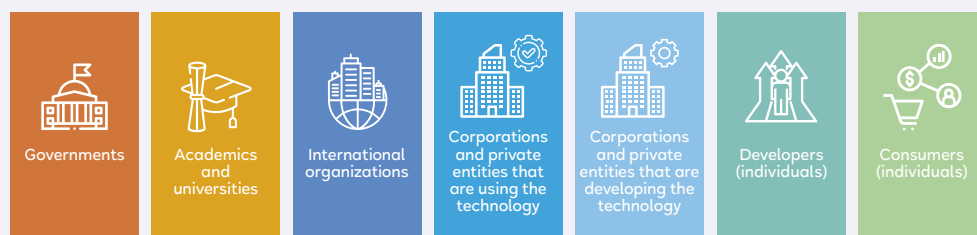
Figure 03 Quantum computing stakeholders (Source: World Economic Forum)

To identify impact areas, WEF first identifies key stakeholders based on their interests. Below is an example of different stakeholder groups in the implementation of a technology.

It then identifies key core values and themes. Within each theme, objectives, opportunities, and negative impacts are identified that together form the basis for the formulation of principles and associated actions.

Core values
In the WEF report, the authors identify some core values that should form the basis for the development of quantum technology. The WEF states that it is important for stakeholders to consider these core values when developing an application.

Below we list the most important core values from the World Economic Forum (WEF) report:[29]

Contributing to the Common Good
Conduct an analysis of how the intended application of quantum technology can contribute to the wellbeing of society. The application should be harnessed to benefit humanity.

Accountability
The application must be designed and implemented so that an organization can be held accountable for its impacts and the organization is able to manage those impacts. This means mitigating negative impacts and enhancing opportunities. It is not just about the design of the technology, but also its use and results. On the other side, society has set up institutions that impose sanctions on organizations that evade this accountability or fail to act when the consequences are negative.

Inclusivity
When assessing the impact of technology and analyzing its potential contribution to society, organizations should strive for inclusiveness. This should include a diverse range of stakeholder views. The goal is meaningful dialogue and to avoid overly narrow definitions of what might be considered harmful or beneficial uses of technology.

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28   https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf

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29   For a full overview of the WEF report can be found here: https://www3.weforum.org/docs/WEF_Quantum_Computing_2022.pdf.

WEF Quantum computing governance principles
Themes and cross-cutting core values
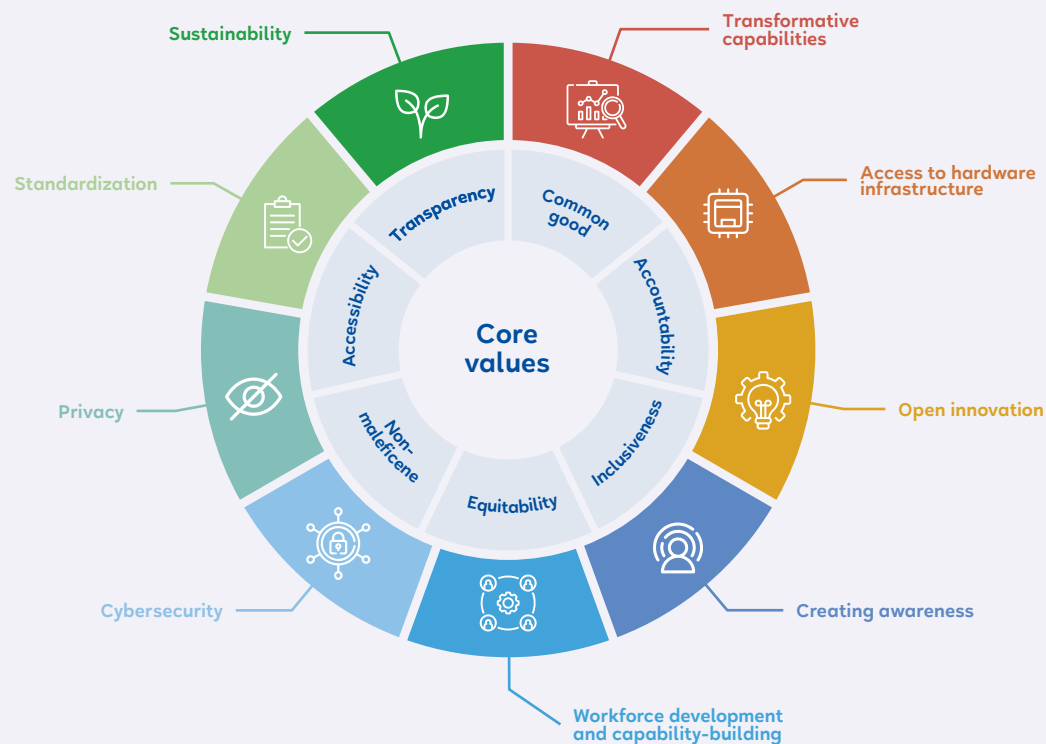
Figure 04 Quantum computing governance principles
(Source: World Economic Forum)

Equitability
Developers and users of quantum technology shall ensure that the benefits of the technology and its impact are distributed fairly and evenly among different groups. Particular consideration is given to any specific needs of vulnerable populations to ensure equitability.

Non-maleficence
Ensure that all stakeholders use the technology in a safe, ethical, and responsible manner so that the technology does not cause harm. All stakeholders ensure that the technology does not endanger people, intended or unintended. To ensure that no harm is caused, data on impact should be collected systematically. For example, an organization might be doing what it is supposed to do — according to legal obligations. However, in view of this value, that does not relieve an organization of the duty to check or monitor the effect of actions taken. Consider the cases often targeted by the National Ombudsman or The Kafka Brigade Foundation — in which organizations comply with their legal duties and carry out their obligations, but entirely unintentionally, still cause harm. This value means, for example, that organizations must gather information about the impact of their actions on stakeholders and intervene when that impact is unintended.

Accessibility
Knowledge of quantum technology and access to facilities to apply the technology (think quantum computing-as-a-service) must be widely accessible to society. This value includes the development, application, and use of the technology. To align with this value, measures are needed around standardization, preventing monopoly positions or dependence on a single party or country. The market must be designed to allow new entrants to enter the market, with new services or products using quantum technology.

An important aspect of accessibility is that quantum technology eventually becomes affordable and usable by all who have an interest in it. This principle may conflict with the interests of governments (military strategic potential of quantum technology) and large parties who have the investment capacity to take over and control the market.
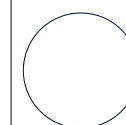
This principle requires government regulation, agreements on being able to share and reuse data and the effective management and control of data by stakeholders. However, it also requires awareness on the part of purchasing that selecting from a large and cheap vendor need not be in the long-term interest of the organization itself, a sector or society.

Transparency
Users, developers, and regulators are always transparent about their purpose and intentions regarding quantum technology.

Other ethical frameworks

Of course, the WEF Principles is not the only ethical framework you can apply to quantum technology. As we saw earlier with AI, many quantum ethics initiatives are currently under development. Moreover, ethics is dynamic, culturally sensitive, and context specific. You can decide which ethical framework you find most appropriate within the context of your application of quantum technology, as long as there is a clear scientific methodology underlying such a framework.

Moreover, it must come from a reliable source (such as the UN, OECD, Asilomar, or the IEEE). An ethicist specializing in technology will be able to assist you in this regard.[30] What is crucial here is that the ethical framework is as quantum specific as possible, supplemented by principles, values, goals, and themes relevant to each system or technology.[31]

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30   This again emphasizes the importance of discussing/implementing EQTA in multidisciplinary teams.

31   Mauritz Kop, *Why we need to consider the ethical implications of quantumtechnologies,* 17 Dec 2021, Physics World, IOP Publishing, https://physicsworld.com/a/why-we-need-to-consider-the-ethical-implications-of-quantum-technologies/.

IN PRACTICE

Step 4: Stakeholder dialogue

The EQTA does not provide a checklist of what is right and wrong, or what is allowed or what is forbidden. The framing of the 'right or wrong' of a technology may lead to its complete embrace or condemnation. This could create the impression that technology and society are opposed to each other, where they are extensively interconnected. Technology can bring benefits to society, for example by improving health care, while at the same time producing negative impacts, for example around privacy. Rather than judging technology in its generality, it makes more sense to guide the application of a particular technology in a specific context in an ethically sound manner.

The EQTA takes this close interconnectedness of technology, people, organization, and society as its starting point.

In the Quickscan, the purpose of the dialogue is to quickly form a view which aspects are relevant and whether a more precise analysis is needed (after the dialogue, step 4, the reader goes back to step 1).

The reader who has gone through steps 1, 2 and 3 has now identified areas of concern from different perspectives: social, technical, organizational, legal, and ethical. This fourth step brings together these concerns and requirements.

The methodology used for both is that of dialogue, in which different people (experts in relevant fields, end users, management and those in the organization who must work with the technology) enter the creative conversation to translate these concerns and requirements from often very different and usually separate domains into concrete approaches.
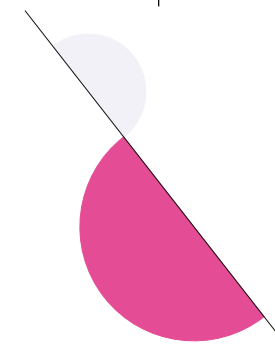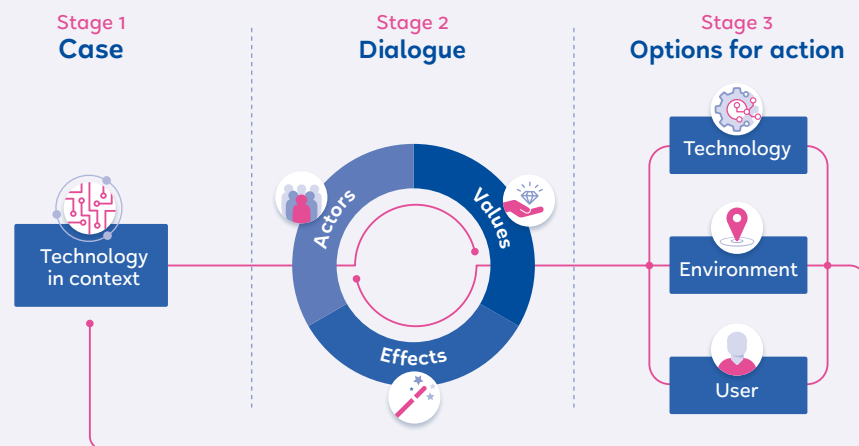
Guidance ethics approach

Figure 05 Guidance ethics approach

Approach to Guidance Ethics

The dialogue uses the Approach to Guidance Ethics to bring together all the different aspects and interconnectedness and provides a (desirable) direction. This changes the question from whether a technology is responsible to how we can develop and use the technology responsibly. In guidance ethics, the focus is not the technology as a whole, but the specific application. Here it is important to describe the context of the technology application as concretely as possible (in step 2 of this step-by-step plan a start has already been made).

The more concrete the application can be described in the context, the more accurately the impact on people and society can be mapped out **(phase 1)**. It is then important to identify all those involved in the application, as well as the positive and negative effects that the technology application has on those involved and the values that are at stake **(phase 2)**.

Finally, it is important to name concrete approaches. This focuses on what measures can be taken to mitigate negative effects and/or optimize positive effects. These may include measures within the technology itself but may also include adjustments in the context or improvements in the use of the technology **(phase 3)**. It is best to discuss these issues in a dialogue format in which all stakeholders participate.[32]

Step 5: Considerations and assessment

To make trade-offs, several proven mechanisms from the legal toolbox can be used: effectiveness, necessity, subsidiarity, and proportionality. These tools are also very useful for making trade-offs about the totality of legal, social, and ethical impact.

Effectiveness
Effectiveness requires assessing whether the proposed action will sufficiently achieve the goal you have in mind. This therefore requires foresight. How likely is it that the deployment of the quantum application will actually achieve the stated goal (or goals)?

Necessity/subsidiarity
In assessing whether a quantum application is necessary and subsidiary, all tools available to achieve the stated goal(s) must be considered. It must then be determined whether the intended application is the least intrusive means of achieving that goal(s).

Proportionality
The final step in the assessment is to determine proportionality. The question of whether an application is proportionate is related to the impact of the quantum application on the individual, versus the importance of the societal goals being pursued. In other words,

32   Approach Guidance ethics: https://ecp.nl/wp-content/uploads/2020/11/Guidance-ethics-approach.pdf.

it is a trade-off between the impact on individuals on the one hand and the interest being pursued on the other. Overall, for a more important goal, more is permissible.

## Step 6: Commitment and accountability

It is advisable to record the outcomes of the steps taken. First, this serves as reference and assurance of decisions made for the design and further development of the application. In addition, recording the steps taken can help to better substantiate decisions and considerations.

Step 7: Feedback and periodic evaluation

The final step focuses on feedback and evaluation. Chances are that your quantum application is still under development. Therefore, it is advisable to periodically reflect on the ethical and social justification of the technology application. Regular evaluation creates a feedback loop that improves the application of quantum technology and makes it more effective. In this step, also clarify the how you intend to achieve this feedback loop.
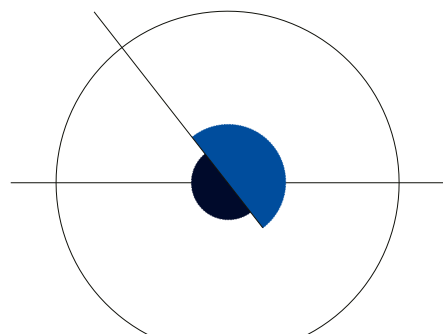
"QUANTUM TECHNOLOGY SETS NEW QUALITY REQUIREMENTS FOR TECHNOLOGY."

03

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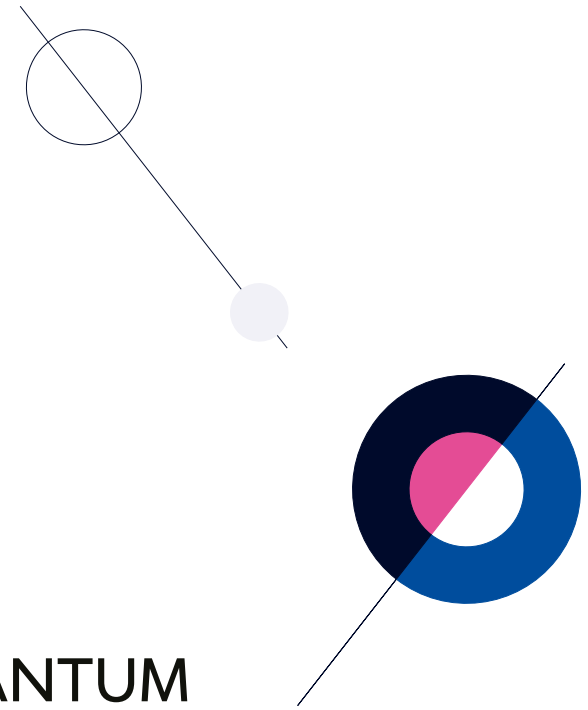
QUANTUM TECHNOLOGY EXAMPLES

Although quantum technology holds great promise, many applications are still in a research or exploratory phase. Developments in quantum technology are mostly taking place in a laboratory environment, for now.

However, there are also more and more ideas and initiatives to apply quantum in practice. In case you do not yet have a concrete idea of the potential applications of quantum technology, in this last section we briefly examine a number of quantum initiatives from practice.

Many organizations are taking steps to acquire competencies in the field of quantum technology. Larger organizations will often have teams dedicated to investigating opportunities and potentially negative impacts of new technologies. In many cases, they are looking at how quantum technology can be used to achieve their goals. In addition, a growing number of organizations see quantum

technology coming their way and are sometimes concerned about the negative impacts. For instance, there may be issues regarding encryption.

In the final part of the Exploratory Quantum Technology Assessment (EQTA), we look at examples of organizations preparing for quantum technology. Some applications are near at hand and require concrete action already. Other applications are even further away with organizations making initial explorations into the possibilities (see) How far along different types of applications are).

Because concrete applications are also still in their infancy, we are not yet talking about use cases or scenarios, but rather examples. In the following sections, therefore, you will find some examples of organizations preparing for the arrival of quantum technology. How are they taking advantage of the opportunities? And how are they preparing for any negative effects?

QUANTUM SENSING AND WATER QUALITY

The Ministry of Infrastructure and Water Management is closely following the development of quantum technology. First, the ministry is focusing on scenarios for making the government quantum secure. In addition, the ministry is looking at the opportunities of quantum technology: a special team is currently exploring the possibilities for applying quantum technology for monitoring surface water.

Surface water quality is now largely measured by taking samples, which are then sent to the laboratory. Measures can then be taken based on the results. In addition, it is not possible to measure all chemical compounds. This makes it challenging to take timely and appropriate action, especially in the case of potential public health hazards.

Governments and water companies are responsible for water quality. If governments and water companies cannot perform this task properly, it can lead to threats to public health, the reduction of food production, the blocking of economic growth and, finally, reputational damage. Due in part to intensive land use, the high population density in the Netherlands, and discharge to water of chemicals such as PFAS, the water quality of the Netherlands is under pressure. Major pollution sources that need to be addressed include manure and pesticides from agriculture. Contaminated water is not suitable as drinking water because of adverse health effects. An additional problem is that it is difficult and costly to make the water suitable for human consumption.

Mapping distribution of pollution
Quantum technology combined with Artificial Intelligence (including Machine Learning), sensors and simulations may be able to help provide insight into pollution and how pollution spreads through water.

Scientists are currently working on hyper-sensitive quantum sensors that can measure in real time which substances or chemical compounds are present in a liquid. Machine Learning is already being used to build models that can predict dispersion of substances in surface water. It is expected that quantum computing can (eventually) make Machine Learning more powerful and faster. This way, quantum technology could make a significant contribution to water quality. For example, this technology may provide much better understanding of water quality while keeping the costs of water quality monitoring, water treatment and enforcement manageable.

PILOT SECURE COMMUNICATION NETWORK PORT OF ROTTERDAM

The port of Rotterdam is experimenting with the application of quantum technology. In doing so, the port sees opportunities especially in the field of secure communication. Among other things, the port authority wants to experiment with a quantum network to communicate securely with various users. This includes, for example, communication with harbor masters and customs. This way, the port authority hopes to prevent misuse of its critical infrastructure. Securing communication systems can increase the safety of sea-going vessels and improve the resulting economic traffic.

The port of Rotterdam represents an important part of the Dutch economy, handling nearly 15 million sea containers a year. This makes it one of the largest ports in the world. The total economic added value of the port is 8.2% of Dutch GDP (63 billion euros) and employs more than 500,000 people directly and indirectly.

Substantially increase security
The port authority manages a critical infrastructure on which Dutch society is highly dependent. In doing so, the port authority uses crucial data necessary for the safe transit of ships, people, and cargo. This includes, for example, measurement of water levels. If this can be tampered with by hackers, the consequences could be devastating.

By using quantum properties, it is possible to detect whether keys have been intercepted during transport over the network. Those secret keys are then used to encrypt information at the sender and decrypt it at the receiver. The encrypted information is otherwise transmitted over the 'regular' Internet.

Based on this new technology (the protocol was already developed in 1984,[33] but application in practice only followed in the last decade[34]) data can be exchanged between a selected number of parties in the port in a protected environment. The Port of Rotterdam Authority, Portbase (an initiative of the ports of Rotterdam and Amsterdam that digitally connects companies and organizations with the ports) and several nautical service providers will participate in the test. The purpose of the experiment is to further validate the technical capabilities of the system. The strength of the chosen setup is the ease with which it can be expanded to include many more users at relatively low cost.

PREPARING QUANTUM-SECURE ENCRYPTION IN THE GOVERNMENT AND FINANCIAL SECTOR

As mentioned above, there are many organizations that are dealing with quantum technology in ways other than applying the technology themselves. For example, quantum computing may eventually cause the cryptography currently used in many Internet protocols to become inadequate. For this reason, there is increasing attention to quantum-secure cryptography. That is, cryptographic technology that a quantum computer is unable to crack. It sometimes seems paradoxical that today's ordinary computers and phones can already perform quantum-secure encryption: quantum-secure cryptography does not require quantum computers.

33   https://en.wikipedia.org/wiki/BB84

34   https://en.wikipedia.org/wiki/Quantum_key_distribution
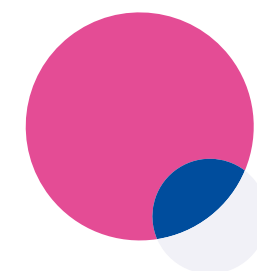
The U.S. National Institute for Standards and Technology (NIST) recently selected encryption methods that cannot be cracked by a quantum computer. These methods are being tested worldwide and will eventually lead to a standard for quantum-secure cryptography.

Several organizations are already busy preparing for a migration to quantum-safe encryption. This includes the central government. This is done to protect against so-called 'store now, decrypt later' attacks. Hackers store the encrypted confidential information now: 'store now' — once the encryption can be cracked with a quantum computer, the information is then decrypted: 'decrypt later'. To make this type of attack more difficult, the government is working on a data migration plan to protect state secrets and other information that needs to be protected for longer periods of time by encrypting it with quantum-secure encryption.

Joint approach

A government-wide plan is currently being developed to collectively address this threat. The goal is a quantum-secure government. The Dutch Banking Association (NVB) is also working with banks in the Netherlands to raise awareness about the possibilities and negative effects of quantum technology within the financial sector.

A major focus is ATMs: they have a lifespan of more than 10 years and must be prepared to run new encryption methods that are quantum secure. Thus, the NVB regularly holds seminars on this topic and various training courses have been developed for bank employees and managers in the financial sector. The NVB also maintains contact with its counterparts abroad on this issue. After all, implementation of new standards requires international cooperation.
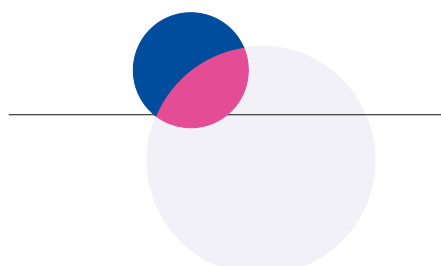
EXPLORING QUANTUM TECHNOLOGY IN THE FINANCIAL SECTOR

Besides the awareness surrounding the negative effects of quantum technology in encryption, case studies are also being developed in the financial sector to explore the possibilities of quantum computing. They are looking at the option of using quantum algorithms for optimization to better predict interest rates in stock trading. Quantum computing can also offer interesting applications in optimization, for example in portfolio management and Machine Learning.[35]

The development in the field of significantly more accurate and fast atomic clocks and oscillators (circuits) will enable much faster global trading.

In addition, quantum algorithms for optimization and (Monte Carlo) simulations on quantum computers could potentially play a role in detecting suspicious transactions under the Anti Money Laundering (AML) legislation — in the future.

Secure authentication and authorization

Another important issue is the possibility of secure authentication and authorization using quantum technology. Quantum technology offers new methods of encryption (see the earlier example on page 78: *Pilot secure communication network Port of Rotterdam*). In addition, there will be new methods for unambiguously determining whether data is being exchanged with the right machine and whether that machine is being operated by the right person.

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35   For instance, optionpricing en other applications (Orús, Román, Samuel Mugel, and Enrique Lizaso. *Quantum computing for finance: Overview and prospects.* Reviews in Physics 4 (2019): 100028.) - https://doi.org/10.1016/j.revip.2019.100028.
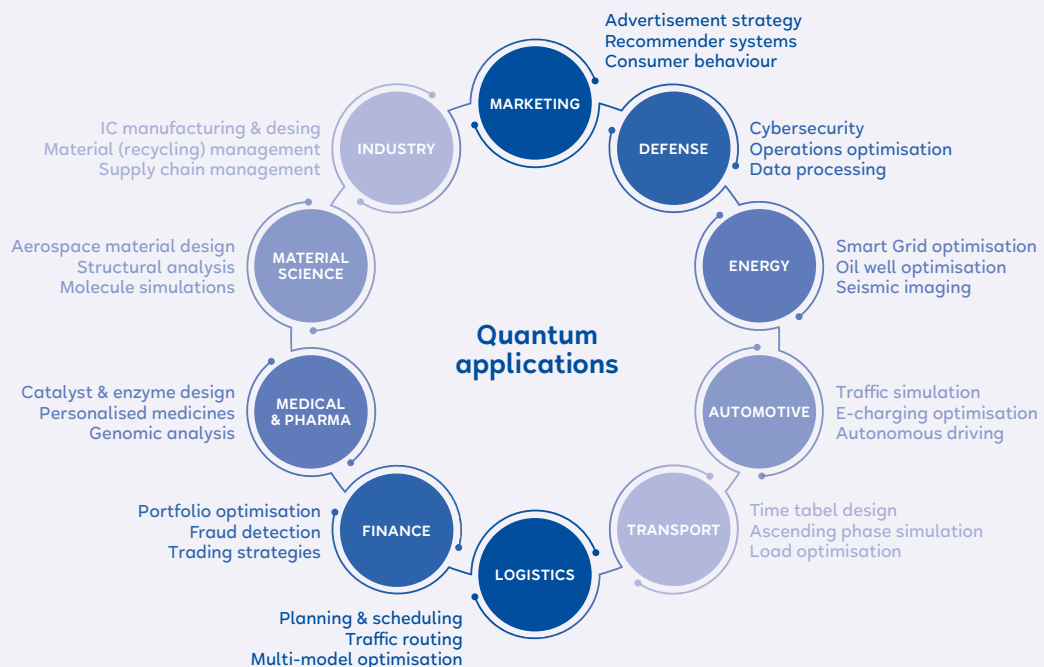
Quantum applications

Advertisement strategy
Recommender systems
Consumer behaviour

MARKETING

INDUSTRY

IC manufacturing & desing
Material (recycling) management
Supply chain management

DEFENSE

Cybersecurity
Operations optimisation
Data processing

MATERIAL SCIENCE

Aerospace material design
Structural analysis
Molecule simulations

ENERGY

Smart Grid optimisation
Oil well optimisation
Seismic imaging

Quantum applications

MEDICAL & PHARMA

Catalyst & enzyme design
Personalised medicines
Genomic analysis

AUTOMOTIVE

Traffic simulation
E-charging optimisation
Autonomous driving

FINANCE

Portfolio optimisation
Fraud detection
Trading strategies

TRANSPORT

Time tabel design
Ascending phase simulation
Load optimisation

LOGISTICS

Planning & scheduling
Traffic routing
Multi-model optimisation

Figure 06 Quantum applications (Source: TNO)

# QUANTUM TECHNOLOGY IN THE TELECOM SECTOR

The telecommunications industry will be affected by quantum technology in several ways. In this section, we list some developments, in the areas of quantum sensing, quantum communications, quantum computing and quantum encryption.

Quantum sensing

First and foremost, the new generations of quantum sensors — and atomic clocks in particular — will soon become part of the infrastructure (Technology Readiness Level (TRL) 6: experiments in the relevant environment. See for further explanation of TRL). As equipment in the networks operates much more accurately and at higher clock speeds, and can also be synchronized accurately, transmission capacity will also increase.

Indeed, a major limitation to the current transmission capacity and processing capability of equipment is the relatively inaccurate measurement of time. The components of devices and in networks are tuned to each other by clock pulses: with each 'tap,' a command is executed. The data packets are given (relatively imprecise) time stamps. As the time pulses become more exact, the frequency of command execution can also increase, and the time stamps also become more accurate.

In the past, the pace of events was determined by the clock tower that struck once every hour, and at a later stage once every fifteen minutes. Now the pace is determined by minutes: everyone has a clock that is accurate to the minute. The same applies to devices: the more precise the time measurement, the more frequent the pulses and thus the synchronization.
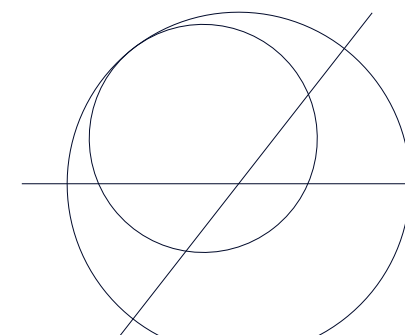
Sensitive quantum gravity sensors will allow much more accurate mapping of the subsurface for infrastructure maintenance and construction (TLR 4).[36]

New generation antennas

Quantum technology may in future enable a new generation of antennas[37] that is not only many times more sensitive, but, in the long run, may also be simpler, cheaper, and more robust (this application has the lowest readiness level, TRL 1: the operation of the principle has been demonstrated in a laboratory). It is expected that the application of quantum sensors will find a place in, for example, radio technology (and thus the radio spectrum) and autonomous navigation.

Quantum sensors are expected to be many times stronger and more accurate than current receiving devices due to their greater range. A related expectation is that quantum sensors will thereby enhance existing applications across the entire bandwidth of the radio spectrum. This applies both to GNSS (Global Navigation Satellite System) location determination and to mobile communications between devices.

In addition, the application of quantum sensors could replace existing radio applications or introduce completely new uses of frequency space. Ultra-sensitive, low-energy quantum sensors are expected to be installed in various places to measure all kinds of properties of air, water, and soil. This will lead to significant challenges for the telecom infrastructure: safely transporting all this data will require major investments.

"Quantum machine learning will recognize hidden patterns in datasets."

Quantum communication

Quantum Key Distribution enables more secure encryption and safer ways to authenticate and authorize. This involves using fiber-optic infrastructure to transmit quantum particles.[38] Telecom providers have a role to play in developing this infrastructure.

Communication between quantum computers will eventually take place over this network as well. This means that with a regulatory body such as the Dutch National Inspectorate for Digital Infrastructure (formerly Radiocommunications Agency as of Jan. 1, 2023) — which deals with the security and reliability of digital telecom infrastructure and the continuity of organizations that depend on IT — telecom providers should at least be aware of the latest relevant developments. The geopolitical aspects (dependence on global players and large tech parties) may already require action while the technology is still developing.

Quantum computing

The telecom sector will be able to leverage the increase in computing power of quantum computers to address optimization problems for, for example, network load control, maintenance planning and

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36   https://www.nature.com/articles/s41586-021-04315-3, https://www.nobelprize.org/uploads/2018/06/popular-physicsprize2012.pdf

37   https://www.forbes.com/sites/moorinsights/2020/04/30/big-atoms-make-small-super-sensitive-quantum-receivers/?sh=6c2cb737740c, https://www.army.mil/article/212935/army_researchers_make_giant_leap_in_quantum_sensing over: David Meyer, Kevin Cox, Fredrik Fatemi, Paul Kunz, "*Digital Communication with Rydberg Atoms and Amplitude-Modulated Microwave Fields*", App. Phys. Lett. (R) 112, 211108 (2018). [arXiv:1803.0354] - https://arxiv.org/abs/1803.03545.

38   Via de lucht (satellieten) kunnen deze deeltjes ook worden verzonden en in theorie zelfs fysiek.

prevention, and network design.[39] Quantum Machine Learning can recognize patterns in large data sets that are currently hidden.

This does presume cooperative collaboration, because without taking precautions in the Netherlands — and perhaps throughout Europe — the principle applies: 'the winner takes it all'. In that case, the telecom provider that has access to the most data would become the largest and could provide the best services in this area.

Quantum-secure encryption
Like the government and the financial sector, telecom providers will have to take measures as early as the next few years to ensure that networks and equipment will be quantum secure a decade from now. This means that the encryption methods used cannot be cracked by quantum computers.

"QUANTUM TECHNOLOGY ENABLES NEW WAYS OF ENCRYPTION."

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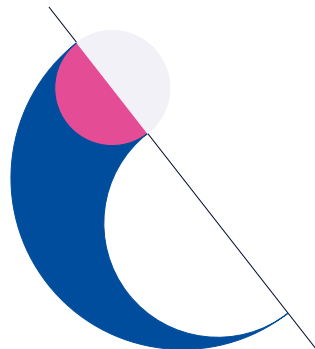
39   En ook hier gelden voornamelijk realtime aspecten: hoe kunnen realtime metingen gebruikt worden voor self-configuratie van het netwerk, bijvoorbeeld gebruik makend van QML. De publicatie is (niet-academici) te downloaden via: https://www.mdpi.com/2073-431X/10/6/71.

APPENDIX 01

QUANTUM TECHNOLOGY IN BRIEF

This chapter briefly describes what quantum technology is, and its applications.

A key question is that regularly arises: how far along is the technology? To this end, we introduce the concept of Technology Readiness Levels. An important source for this chapter is the publication 'The impact of quantum'[40] (July-2021), by Birch, commissioned by Quantum Delta Netherlands and Innovation quarter Zuid-Holland.
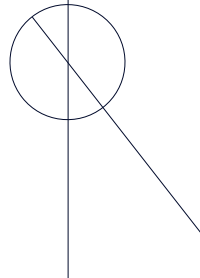
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40   https://www.quantumforbusiness.eu/insights/birch-quantum-impact

TECHNOLOGY READINESS LEVELS (TRL'S)

Because different applications of quantum technology vary widely in maturity, the concept of Technology Readiness Level (TRL) is used. This concept was developed by NASA[41] and is now widely used to indicate the maturity of a technology. At TRL 1 (the lowest level of maturity), only the basic principle that the application uses has been observed. One or two levels higher, the feasibility is also examined. From level 4, the technology is actually developed, and at levels 5 and 6 also demonstrated. At level 6 through 9, systems and subsystems are also developed. At TRL 9 (the highest maturity level), the system is also tested and ready to be implemented.

WHAT IS QUANTUM TECHNOLOGY?

Quantum technology is based on the laws of quantum mechanics: the laws that describe the behavior of particles at the level of atoms, photons, electrons, and molecules. Technological developments in recent decades have made it increasingly possible to measure and specifically influence the behavior of these particles.

The phenomena described by the laws of quantum mechanics have puzzled scientists for several centuries. The laws of quantum mechanics describe the phenomena in such a way that they can be predicted. The first complete description of the phenomena by physicists is almost a century old (if we take the 1927 Solvay Conference [42] as a milestone).

Technology readiness levels

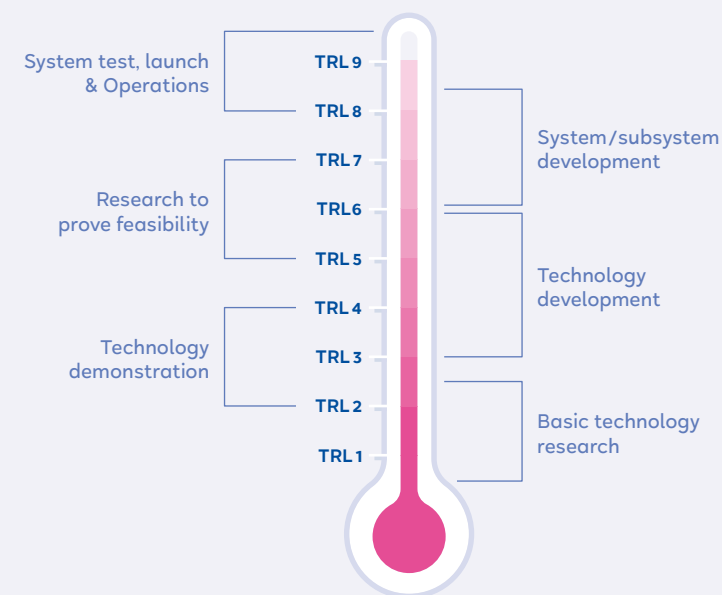| System test, launch & Operations | TRL 9 | |
	TRL 8	System/subsystem development
	TRL 7	
Research to prove feasibility	TRL 6	
	TRL 5	Technology development
	TRL 4	
Technology demonstration	TRL 3	
	TRL 2	Basic technology research
	TRL 1	

Figure 07 Technology Readiness Levels

In recent decades (and especially in recent years), technical developments have progressed to the point where we can not only observe and describe the behavior of these particles, but also increasingly learn to control and direct them. This leads to a large number of new applications. The latter is the reason for writing this Exploratory Quantum Technology Assessment (the EQTA).

41   https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html

42   https://en.wikipedia.org/wiki/Solvay_Conference (consulted 10/18/2022).
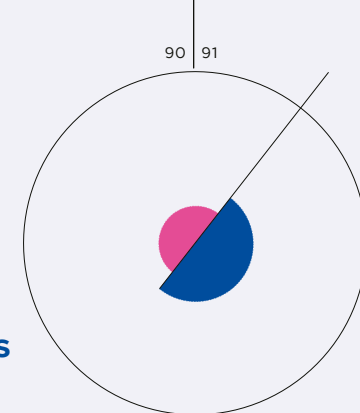
Incidentally, it is important to remember that being able to describe, predict and even manipulate the behavior of the smallest particles is very different from understanding the behavior. The words that quantum mechanics uses to describe phenomena are not necessarily explanatory: think of words strongly associated with quantum technology such as 'quantum entanglement' or 'superposition'.

They are concepts for describing and predicting the behavior of particles. These concepts can be compared to the law of gravity: the law of gravity says nothing about the mechanisms that cause gravity, but it allows us to describe and predict the behavior of objects here on Earth. Since no one is surprised by objects falling, no explanation (in words) is needed. We think the same will be true of quantum mechanics: once we get used to the applications of quantum technology, only scientists will ask questions about why.

Using words to describe the behavior of particles quickly leads to misunderstanding. Such words therefore contribute to the mystification of quantum technology. Consider phrases such as 'quantum particles that are in two places at once' or 'quantum particles that acquire properties only when observed'. Or that in quantum entanglement one entangled particle 'communicates' information with the other entangled particle 'faster than light'.

This type of explanation (in words) is not, we believe, necessary to understand applications (and the limitations) of quantum technology, and so this chapter refrains from such a description. After all, even from an 'ordinary' computer or cell phone, it is incomprehensible to most people (how using only the values 0 and 1 can create such complex functionality). We therefore focus in the EQTA on the functionality of quantum technology and not on providing an understanding of the laws of quantum mechanics.
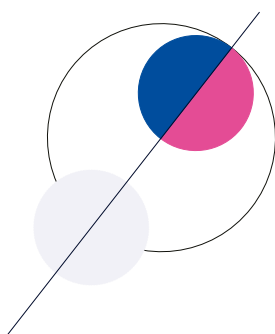
WHAT CAN QUANTUM TECHNOLOGY DO?

Being able to measure, control and direct the behavior of quantum particles leads to three types of new applications: quantum sensors, quantum networks and quantum computers. Quantum-secure encryption is discussed in the last section: this issue affects the whole of society, regardless of whether an organization adopts quantum technology.

Quantum sensors

By using the laws of quantum mechanics, a new generation of very precise, robust, and perhaps more affordable sensors becomes available. Those sensors can be used, for example, to measure properties such as time, motion, acceleration, dimension, gravity, current and voltage.

Applying these sensors creates opportunities for organizations to do things that are new, different, or better. Taking advantage of these opportunities requires adjustments within organizations and requires new collaborations between organizations. Being able to quickly measure all kinds of properties easily and highly accurately leads to ethical and legal questions: what is desirable and necessary? What safeguards are needed? The EQTA helps organizations think about these questions.

Applications in a variety of domains

It is difficult to estimate how big an impact quantum sensors will have on equipment functionality and—insofar as these sensors lead to lower costs for measuring these properties—to widespread application in electronics. Quantum sensors will find application in professional equipment in a variety of fields, including healthcare, logistics, construction, and telecom. For example, images from MRI scans will be able to achieve higher resolution. By precisely measuring very small differences in gravity, we will gain a better understanding of what is in the subsurface. Quantum sensors will be able to register

motion and acceleration more accurately, allowing objects to be located much more precisely in space, even without GPS.

Lasers will become more accurate and energy efficient because quantum sensors can also register small amounts of reflected light particles. This has implications for recognizing properties of liquids and materials: they may eventually be able to be measured much faster and cheaper.

Faster and more accurate

As quantum technology enables more precise measurement of time, it will lead to all kinds of noticeably faster applications. GPS will become many times more accurate because of this. The quantum sensors enable faster clock pulses (oscillators), and thus faster timing of execution of commands by processors and faster information exchange between the components of computers, telephones, and all kinds of devices.

Better synchronization also enables faster information exchange between systems in wired and wireless telecom networks. With these more accurate sensors, chip sizes may be reduced even further. Perhaps these sensors will lead to a new generation of sensitive — and technically much simpler and more robust — antennas.

Timeline: The development of these sensors using quantum technology is moving very quickly. Some applications (such as quantum clocks) are already coming to market.[43] Many of the quantum sensors measuring properties are under development in laboratories.

Quantum networks

In the area of security and communication, new functionality will gradually be added to networks we know today (through fiber, by air and/or by satellite), over the next few decades. This will enable more secure exchange of highly confidential information. Currently, there is a lot of focus on being able to exchange encryption keys confidentially: Quantum Key Distribution.

Quantum networks also offer possibilities for authentication and authorization (establishing with certainty the identity of receiver and sender and the machines they use).

Robust measures

It is worth remembering that confidentiality during the transportation of information and being able to determine the identity of the sender and receiver with greater certainty are not enough to ensure confidentiality of information exchange. But quantum technology does enable newer, more robust measures in an increasingly complex set of measures.

Quantum communications will eventually make it possible to connect quantum computers to form a larger quantum computer and thereby enable distributed quantum computing.

Timeline: These communication applications for secure exchange of information (Quantum Key Distribution) will come to market in the next few years or are at an experimental stage (TRL 4-6). Standardization of secure encryption key exchange is at an advanced stage.[44] Getting processors of quantum computers to work together over networks will require a longer period of time.

43   Ortt, R. (2020). *De Technologie-monitor 2020 Quantumtechnologie*. Stichting Toekomstbeeld der Techniek, Den Haag. - https://stt.nl/nl/toekomstverkenningen/97-de-technologiemonitor-2020-quantumtechnologie/nationale-technologiemonitor-2020-quantumtechnologie.

44   https://www.standict.eu/discussion-groups/quantum-computing/297/towards-european-standards-quantum-technologies

Quantum computers

The promise of quantum computers is that a number of specific problems can be solved much faster with the quantum computer than with classical computers. In doing so, four types of applications are commonly identified:

- **Simulating the behavior of atoms**
Simulating the behavior of the simplest atoms is quickly too complex for current computers. However, quantum computers can be used to simulate the behavior of molecules and atoms (for drug and material development and for a variety of chemical and biological processes).

- **Solving specific problems more rapidly**
Quantum computers can solve certain problems faster. Consider optimization problems, where many different solutions are possible, each of which must be computed. Examples include traffic, logistics, finance, and healthcare. Searching large unstructured data sets may also be faster with quantum computers.

- **Rapidly breaking encryption of digital communications**
The encryption algorithms that are common today derive their power from computational problems that cannot be solved efficiently without knowing the key. However, some computational problems that current computers cannot solve now will soon be solvable by quantum computers. This means that a number of the encryption (and authentication) algorithms that are commonly used today will no longer be secure in the quantum computer era.

- **Machine Learning**
In the field of Artificial Intelligence (AI), Machine Learning will benefit from quantum computers.[45]

Number of qubits in quantum computing (figurative)
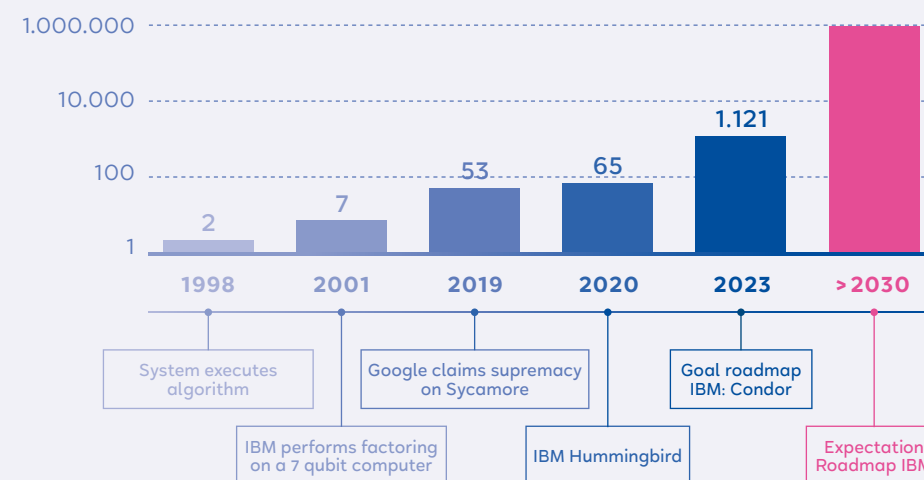
Timeline: (see Figure 08) Currently, small quantum computers are available for experimental use and for gaining experience with their features. Major breakthroughs still need to occur before serious applications of the quantum computer will become viable: both in computing power and in basic things like quantum memory and data storage. The electronics needed to drive and embed a quantum computer are still under development. Algorithms and software are also still being worked on around the world.

Yet even this observation about quantum computing is not entirely true: there are also ways to use the quantum computer in a heuristic sense to solve certain problems. That is, as a practical way to quickly arrive at a result without having to compute solutions all the way through. This type of application is more likely to be within reach.

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45   Neumann, N., Phillipson, F. & Versluis, R. *Machine learning in the quantum era*. Digitale Welt 3, 24-29 (2019). https://doi.org/10.1007/s42354-019-0164-0.

Quantum-secure encryption

Even though it will be at least a decade before quantum computers are fit for purpose, society should anticipate their upcoming arrival now. After all, quantum computers have been proven to be able to crack the encryption methods commonly used today. Fortunately, we do not need quantum computing power to use quantum-secure encryption. The weaknesses in current forms of encryption can be fixed without using quantum computers.
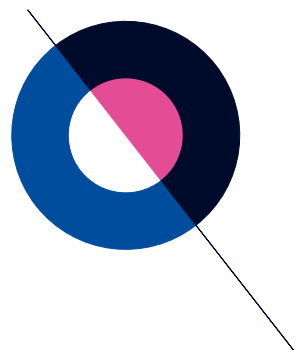
Much of the information that must remain confidential for longer than 10 years must therefore be quantum securely encrypted now. Devices and machines that have a lifespan over 10 years will already have to be equipped with encryption methods that are quantum secure. Think of ATMs in the street, bridges and locks in public spaces, or archives. The standardization of quantum-secure public-key encryption methods by NIST [46] (National Institute of Standards and Technology) is at the conceptual stage. In the coming years, these methods will be used in a variety of services and products.

The transition to new methods of encryption is a major area of concern for organizations, with some organizations anticipating the need to begin working with other organizations in the sector. Especially around ATMs, public-space equipment and archives mentioned earlier, best practices and guidelines need to be established quickly. Other organizations need to start encrypting information in such a way that it can be securely re-encrypted when needed. The knowledge and resources will not be available to every organization, and many of these developments will require closer collaboration.

"QUANTUM SENSORS WILL FIND APPLICATION IN PROFESSIONAL EQUIPMENT IN A VARIETY OF FIELDS, INCLUDING HEALTHCARE, LOGISTICS, CONSTRUCTION, AND TELECOM."

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46   https://csrc.nist.gov/Projects/post-quantum-cryptography/post-quantum-cryptography-standardization

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