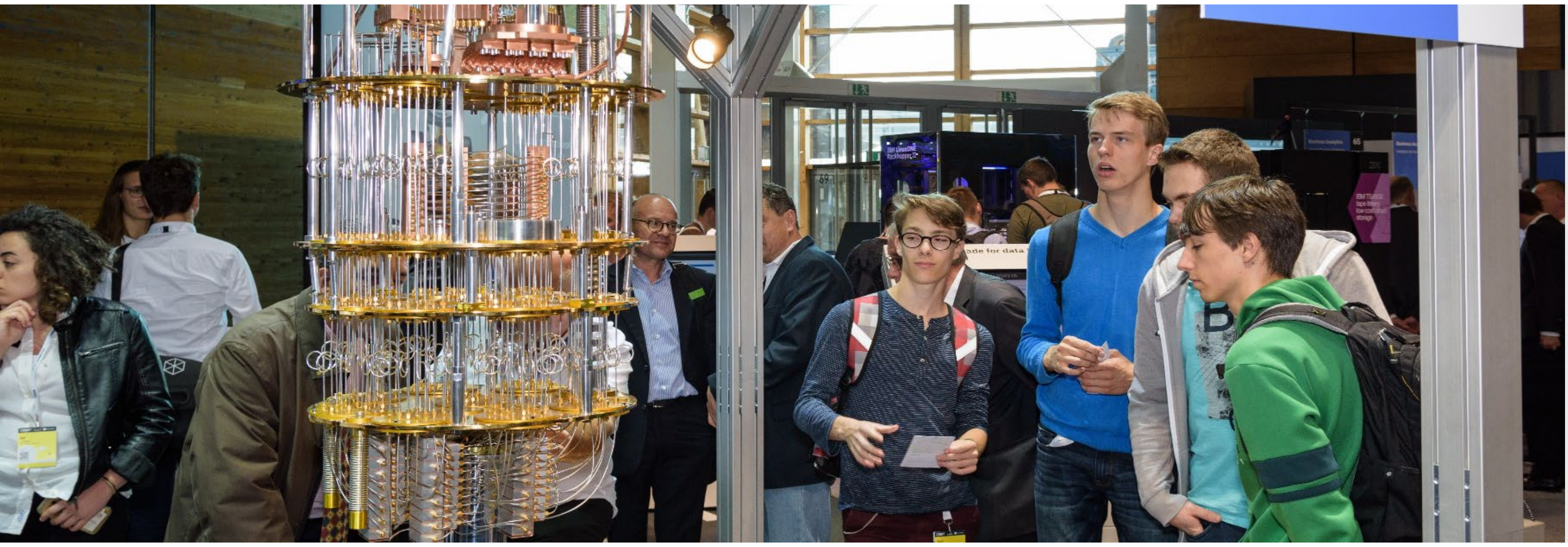
Rathenau Instituut

Quantum Technology in Society



Rathenau Scan

Introduction

Quantum technology brings to mind the image of a digital revolution ushering in a new era in digital society. Quantum computers are expected to calculate much faster than conventional computers, with almost unlimited possibilities, while a quantum Internet is said to be far more secure and functional than the current Internet. The Netherlands has expressed the ambition of becoming a *Silicon Valley* for quantum technology.

But will quantum technology in fact be such a gamechanger? In this Rathenau Scan, we attempt to answer that question in a series of steps. First we consider technological development (*What is it?*). We then go on to survey the potential applications (*What can it do?*), describe the innovation landscape (*Who is doing it?*), and address the societal issues raised by quantum technology (*What do we need to watch out for?*). Finally, we provide an answer to the basic question and look forward to the future (*How to proceed?*).

Contents

1. What is it? Quantum technology 2.0 — 2
2. What can it do? Promising applications — 7
3. Who is doing it? The Dutch innovation system — 12
4. What do we need to watch out for? Public values — 15
5. How to proceed? — 22
6. Sources — 24

Quantum technology in society

Specific applications

Computing

Greater computing power

Pattern recognition

Optimalisation

Solving complex mathematical problems

Simulation

Modelling natural processes:

Biochemical processes

Healthcare

Simulations

Communication

Security & greater functionality

Quantum internet

Sensing

Precision measurement, higher resolution:

Dark matter

Seismology

Microscopy

Public concerns

Cyber security

- Online encryption can be broken
- Quantum Key Distribution: internet possibly more inaccessible

Privacy protection

- Decryption: personal data disclosed
- Surveillance by governments and companies

Military security

- Development of biological weapons
- Increased precision weapons
- Expansion of surveillance tools

Justice

- Increasing concerns about profiling with AI
- Increase in unequal distribution of power and wealth ('quantum divide')

Strategic autonomy

- Power concentration intellectual property
- Commercialisation of fundamental knowledge
- Need equal playing field

Knowledge security

- International knowledge sharing is needed, but can hurt security, privacy, and economic opportunities

Trust in experts

- Expertise gap: dependence on very small pool of experts
- Talent gap: shortage of qualified professionals

Sustainability

- It is still uncertain whether quantum technology reduces or increases energy consumption

1. What is it? Quantum technology 2.0

1.1. Quantum technology is not new

The early twentieth century saw the advent of modern physics. Besides a new understanding of gravity through the theory of relativity, modern physics is based on the study of minute entities: matter and energy at the scale of molecules, atoms, and subatomic particles (such as electrons, protons, photons, and quarks). The smallest, indivisible unit of matter or energy is referred to as a “quantum”, and this field of study has hence come to be referred to as quantum mechanics.

Knowledge of quantum mechanics gave rise to quantum technology, which is used, for example, in semiconductors (the building blocks of almost all electronic devices), lasers and MRI scanners, and for charging batteries. Without quantum technology, computers, smartphones and the Internet would not exist. This technology comprises, for example, magnetic field resonance (MRI scanners), stimulated photon emission (lasers) and doping, i.e. deliberately "contaminating" the basic material by adding foreign atoms to it, thus making it unstable and modifying its electrical properties (semiconductors).

Such quantum technology does not yet exploit certain specific properties of quantum particles – such as superposition, interference, and entanglement – whereas the technology we are dealing with here does do so, and is sometimes referred to as “quantum technology 2.0”.

1.2. “Weird” quantum properties

Quantum mechanics gives a description of reality in terms of probabilities that does not square with our everyday experience of the things around us. At the quantum level, physical processes operate that can be well understood mathematically but remain hard to grasp intuitively.[1] In order to get a good command of the applications of quantum technology, and the societal questions it raises, a basic understanding of three quantum properties is required.

Superposition

Conventional computers use bits to store information and perform calculations. A bit always has the value of 1 or 0. With this binary system (bit is a contraction of *binary* and *digit*), basically all information can be recorded and processed. Quantum technology 2.0 doesn’t work with bits, but with qubits. These utilise the phenomenon of superposition from quantum mechanics, which dictates that particles are in multiple states simultaneously until a measurement is made. The state of a qubit can therefore be *both* 1 and 0. It is only through measurement that the qubit receives the value of 1 or 0. Qubits are therefore like tossed coins which – until they fall on one side or the other – can be either heads or tails. Exactly how measurements are physically performed depends on the type of qubit. Several types are currently under development (see the overview in Table 1).

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1 A great deal of attention is therefore paid to quantum mechanics in the philosophy of physics; see for example https://plato.stanford.edu/entries/qt-issues/.

Interference

The probability of a qubit being in position 1 or 0 when measured yields a probability distribution that is expressed as a wave pattern. If wave patterns of multiple qubits are made to interact (i.e. to interfere), they either reinforce or extinguish one another, thus determining the state of the qubits concerned. The behaviour of qubits can thus be predicted and calculated by means of mathematical models of wave functions.

Entanglement

If particles have made direct contact with one another, they can continue to share information remotely, regardless of how far apart they are. This phenomenon is known as “entanglement” and has been demonstrated experimentally. For example, if two particles are entangled and the spin (the direction of a particle's angular momentum) of one of them is upward, then we know immediately that the other particle must have a downward spin.

A qubit can be entangled with one or more other qubits. Measuring a single qubit can therefore automatically provide information about the other qubits that are correlated with it. It is important to note that it is *only* complementary information that can be derived from entanglement (i.e. one spin upwards, then also one downwards). It is therefore not the case that any information whatsoever can be shared via entanglement and that it is possible, for example, to exchange information faster than the speed of light.

1.3. The quantum computer

These three quantum properties are utilised in the three applications of quantum technology: computing (including simulation), communication, and sensing. An overview of applications follows in part 2; here we will take a closer look at the quantum computer.

Quantum algorithm

The superposition of qubits exponentially increases the amount of information a system can represent. After all, with two qubits, four states are possible, with three that becomes eight, and so on. Qubits also allow calculations to be performed in parallel. Delft University of Technology (TU Delft) uses the image of an ant colony as a metaphor for a quantum algorithm. One can compare ants that *collectively* and *simultaneously* search for a way out of a maze (let’s say find the answer to a sum) with a single ladybird that has to check out all the possible routes.[2] Time is saved when ants searching along wrong routes are quickly extinguished. That extinction occurs through interference, which reveals the most likely solution.

Calculating probability with interference is carried out by quantum algorithms tailored to solving specific calculation problems. Quantum algorithms also utilise smart

2 TU Delft (n.d.a).

entanglement methods. As a result, quantum algorithms arrive at correct solutions faster than it would take to check all the possible combinations (as the ladybird does).[3]

Software

Quantum computing involves a fundamentally different method of calculation. Nevertheless, quantum algorithms, just like conventional algorithms, consist of a set of instructions that the computer uses to solve a problem. A physical circuit of logical operators (*gates*) must be set in motion in order to manipulate the network of qubits. For example, there are gates that can flip qubits from 0 to 1 but also gates that create a superposition state.

Like conventional software, quantum software consists of several layers. Research is currently taking place on all these layers. It is necessary to translate the machine language into higher-order programming instructions and ultimately into special programming languages and applications. The higher-order layers are "hardware-agnostic", meaning they can run on any type of qubit.[4] The lower-order machine language does vary according to the type of hardware.

Technical challenges

The physical realization of the hardware for networks of qubits is also an active area of research, because it is difficult to construct a quantum computer.

First of all, qubits are highly sensitive to outside interference, and even the slightest microscopic vibration or temperature change can throw the qubit network out of balance (*decoherence*).

Second, it is difficult to keep qubits in a fixed state, so that if calculations are not performed fast enough, the system loses information.

Third, qubits do not always do what they are told to do because they make the wrong rotation (*phase flips*) or become disrupted by information being read out. Reversal to a wrong final state may also occur. Conventional computers sometimes exhibit such *bit flips* too, but qubits are much more sensitive to them.

Fourth, it is difficult to get a lot of qubits to form a network that can perform logical operations without error. This scalability depends on the available materials and on the degree of error sensitivity of the type of qubit.

Several paths are currently being pursued in qubit development so as to address these challenges (see Table 1 for the existing range of qubits). It is currently still uncertain which qubits will ultimately be utilised, or whether multiple types of quantum computers will coexist or even be used interchangeably.

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3 This document provides only a general overview of superposition, entanglement, and interference. A deeper understanding of quantum computing requires a knowledge of linear algebra, a discipline that deals with vector spaces and transformations, such as breaking down a mathematical function into a continuous spectrum of frequencies.

4 Qiskit (qiskit.org), for example, is an open-source Python environment in which commands for quantum calculations can be encoded that can then be executed by multiple hardware providers. However, special higher-order programming languages are also being developed for specific types of hardware such as Microsoft's Q#.

Error detection
The error sensitivity of qubits means that error correction is needed. In some cases, the number of errors can be detected using conventional algorithms, but the extent to which that can be done is limited. A more effective way is to repeat the calculation with other qubits. Because quantum information cannot be copied directly, this can only be done by spreading information, and researchers have developed methods for doing this. With superconducting qubits, it is estimated that a factor of 1000 more physical qubits are needed for 1 logical qubit to work flawlessly.[5] For some types of calculation problems – such as decrypting encrypted data (see part 2) – quantum computers only achieve an advantage over conventional computers (*quantum advantage*) if they are scaled up to several thousands logical qubits. With the superconducting variant, millions of physical qubits are therefore needed to make those computers work flawlessly. We are a long way from achieving that. Currently, IBM seems to be the furthest advanced with its *Osprey* quantum computer, launched in late 2022, which consists of 433 *physical* qubits.

Speed, scalability, and quality
The overview in Table 1 shows that the various development paths each have their pros and cons. [6] Strong insulation of qubits prevents ambient interference, but makes it much more difficult to gain a speed advantage and to scale up effectively. Big technology companies are committing to the type of qubit that they consider to be the most promising. Google and IBM, for instance, are working on superconducting quantum computers, while Microsoft is working on the topological variant. According to most predictions, it will take 15 to 25 years before we have quantum computers that are scalable, fast, accurate, and error-free. Despite the many hurdles that need to be overcome as regards both hardware and software, we can already make a reasonable estimate of the applications promised by quantum technology. We will explore them in the next part.

5 Completely error-free will probably never be possible. However, we can expect errors and noise to be reduced to the point where they no longer affect calculations.
6 Note that hese are the main development paths, next to these some are also being tried out on a smaller scale.

Table 1 **The range of qubits**

Type of qubit	Technique/material	Pros	Cons
Superconducting	Electrons trapped on superconducting chips; Measurement by determining velocity of electrons.	Qubits easy to control; High circuit speed; Same material as conventional chips, meaning production is easy/cheap.	Extreme cooling required (-273°C); cryostats are large and expensive; Short coherence time; Many physical qubits needed for error control; Difficult to scale.
Photonic	Light sources transmit photons through processor network; Calculations by interaction between photons; Measurement by light detectors.	Qubits at room temperature; Extremely long coherence time; Extremely fast; Photons are easy to generate; Suitable for communication.	Sources and detectors of photons do require extreme cooling; Qubits difficult to manipulate and control; Difficult to scale; Low precision.
Trapped ions	Charged atoms and electrons orbiting their nucleus, trapped in vacuum chambers using magnetic fields; Emission and manipulation via lasers or microwave sources; Measurement via fluorescence detectors.	Precise control; Long coherence time; Entanglement easy; Little likelihood of manufacturing defects.	Extreme cooling required; Lots of lasers needed; Qubits must be individually controlled in vacuum chamber; Difficult to scale; Low speed.
Topological	Anions (negatively charged ions) spin as a braid and thus influence one another.	Long coherence time; Few physical qubits needed for error control.	Existence of required anion (for example the “Majorana particle”) not yet experimentally proven.
Quantum dots	Electrons are trapped with electromagnetic fields on silicon (nanometre-sized semiconductor particles); Spin expresses state of the qubit.	Same material as conventional semiconductors, meaning production is easy/cheap; Scalability; High circuit fidelity (accurate).	Qubits difficult to initialise; Qubits difficult to manipulate; Extra-sensitive to noise from electromagnetic charge.

2. What can it do? Promising applications

2.1. Quantum advantage with specific applications

Quantum technology is still largely in the development phase; many envisioned applications have yet to find their way into society. But although we have yet to reach that tipping point, there is already a lot to be said about the promises offered by quantum technology 2.0. Those promises are to be found in *specific* applications. It is unlikely that quantum computing will become the new paradigm of digital computing. Conventional computers continue to be needed alongside quantum computers. Excel and Word will not run faster or better on a quantum computer, and conventional computers will be needed to process data as well as to control and check quantum calculations. Conventional computers are also already very fast; they can perform billions of operations per second. The quantum advantage must therefore come from specific applications. The challenge is to create effective combinations of conventional computing power and quantum computing power.

2.2. Four application areas

The specific applications are to be found in the use of quantum computing power, optimisation, simulation of natural processes, precision measurement, and remote communication. We will discuss the applications according to the common classification into four application areas: computing, simulation, communication, and sensing. But please note that simulation is actually part of computing. Communication and sensing may also overlap with computing, but these areas have their own development paths.

Computing

There is a class of complex calculation problems characterised by an exponential increase in the number of possibilities. These include search problems such as the "traveling salesman problem": given x number of cities, find the shortest route whereby you visit each city only once and end up again at the first city. If x is a large number, it is not feasible to run through all the possibilities; a smart algorithm is therefore needed that takes you along the shortest route. But even with such an algorithm, calculations with conventional computers take an extremely long time, if they manage to produce a solution at all.[7]

An example of such a search problem for the digital domain is factorization: breaking down a number in a product of factors. With large numbers it is practically impossible to determine the two prime numbers of which the number is a product, because the number of possibilities then becomes exponentially large. Much of what happens on the Internet (websites, e-mails, banking traffic) is protected by means of encryption that can only be cracked by factoring large numbers into primes. Ordinary computers cannot solve this calculation problem, but quantum computers are expected to be able to do so, meaning that current encryption will probably soon become insufficiently secure. Since 1994 an algorithm (*Shor's algorithm*) exists for tackling this calculation problem,

7 A network of 100 processors spent 22.6 years (!) calculating a solution to a version of the problem involving some 15,000 cities: https://www.math.uwaterloo.ca/tsp/d15sol/index.html.

and hence quantum software is available for factoring large numbers into primes. Thus when quantum computers become powerful enough, a major threat to cybersecurity emerges.

Many forms of optimisation are expected from quantum computing power. For example, quantum technology can be used within logistics for route optimisation, thus improving supply chain management. In the financial sector, the main focus is on improving risk analysis, for example by using “Monte Carlo simulations”, i.e. simulating a process many times while varying the starting conditions. In artificial intelligence focus is on improving pattern recognition, for example of speech or images. Work is already underway on improved object recognition for self-driving cars and climate models for weather forecasting.[8] There is also “Grover's search algorithm”, which enables rapid search in large, unstructured datasets.

Simulation
A great deal is also expected from quantum technology for simulation of natural processes.[9] Biochemical processes are difficult to capture at the quantum level because of the interactions of large numbers of particles. The new quantum technology is expected to make it possible to simulate processes with greater accuracy.[10] Practical applications of quantum simulation are envisaged in medicine.[11] If molecular interactions within cells can be simulated, it could lead to both improved understanding of diseases and better cure of them. Simulation applications are also being considered within computational biology, materials science, and chemistry, for example for chemical reactions or specific properties of substances. This knowledge can in turn be utilised for optimalization, for example with respect to the generation of energy from natural resources, or to extend the life of batteries.[12]

Communication
Quantum properties may also be utilised for communication. Through entanglement, a network of qubits – or on a larger scale a network of quantum computers – could form the basis of a future quantum Internet.[13] In the current Internet, computers communicate with one another via light signals that transmit a kind of Morse code series of 0s and 1s. In the quantum Internet, information is transmitted via qubits. The Quantum Internet works with a chain of intermediate stations where entangled photons are sent to neighbouring stations. Satellites could play an important role in such quantum networks, because qubits in space suffer far less from interference than on Earth. Another advantage is that quantum networks on Earth can be connected over long distances via satellites.[14]

8 Autovista24 (2022), 1Qubit (n.d.).
9 It has already been shown that non-natural processes can also be mimicked, although the term “simulation” is not generally used for this in the field of quantum technology.
10 Precisely this idea of simulating natural quantum systems by quantum means led the eminent physicist Richard Feynman to think of a quantum computer: Feynman (1982).
11 A useful overview is provided by Schuurmans (2022).
12 A useful overview of the state of research in this field (in 2022) can be found in Paudel et al. (2022).
13 For the road towards creating this, see this roadmap: TU Delft (n.d.b) and also Bouwmeester (n.d.).
14 Aliro Quantum (2021).

For data security, the fact that qubits cannot be perfectly copied (the *no-cloning property*) is an important factor. Consequently, quantum information cannot be intercepted without losing its integrity. As early as 1984, a protocol was developed for *Quantum Key Distribution* (QKD), whereby encryption keys are transmitted via a separate information channel based on the quantum properties of light. Any interference from a third party is then noticed immediately. QKD already has a number of successful implementations. Since late 2022, a new type of quantum network has been undergoing testing for protecting communication in the port of Rotterdam.[15]

Sensing

A final application area where new quantum technology promises breakthroughs is sensing. Quantum technology has long been used for sensing, for example in MRI scanners and in lasers. By measuring the quantum properties of particles, it is expected that higher resolution can be achieved than with existing sensor systems. Quantum sensors will presumably not replace existing measurement systems but will become part of them. Quantum sensing overlaps with other forms of quantum technology, such as simulation,[16] and is closely related to fields such as photonics and optics.

Many applications of quantum sensing are expected, for example in microscopy and seismology. Among these applications is also the even more accurate measurement of time. Since the 1950s, atomic clocks have been the standard for this. They use vibrations of atoms as the basis for time measurement. Those vibrations are extremely constant, and very slight deviations would lead to a divergence of only 1 second in 5 billion years. Synchronising two atomic clocks is a lot more difficult, however. Physicists managed to do so for the first time in 2022 using quantum entanglement. Synchronisation makes atomic clocks even more precise, which is important for GPS measurements. It is also useful for making extremely precise measurements of gravity and in research on dark matter. Another important application that may emerge is navigation using very precise measurement of the Earth's magnetic field, which does not require GPS. This method of navigation can, for example, be used underwater, where GPS signals are not possible.

2.3. Short-term and long-term breakthroughs

Many uncertainties still surround the future of quantum technology,[17] although some differences in pace are revealing themselves. For instance, quantum sensors are at an advanced stage of development, and sensing already has many practical applications. There have also been some breakthroughs with the first practical applications of quantum encryption. Even so, an entire quantum Internet is unlikely to appear in the foreseeable future.

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15 TU Delft (2022).

16 Liu (2021).

17 Predictions regarding breakthroughs in the next 5 years or between 5 and 10 years from now are therefore extremely uncertain and we will not deal with them here.

Certain simulation and optimisation applications seem promising in the short term. It is striking, however, that expectations regarding machine learning vary widely. Some people expect the most spectacular breakthroughs to take place in this field, while others are dampening down this enthusiasm because there is as yet hardly any quantum software that is useful and *also* produces results that are clearly faster than “ordinary” software. They do not expect such a “killer application” to become available in the near future.[18]

Estimates vary widely as to when we will have a quantum computer with a large enough number of logical qubits to run Shor's algorithm, for example. One frequent estimate is between 15 and 25 years from now. On the road to such a machine, there will be more powerful quantum computers which will still, however, have a lot of noise; this is referred to as the *Noisy Intermediate Quantum-Scale era* (NISQ). It is difficult to predict how those computers with noise will be useful.

This does not alter the fact that small working quantum computers already exist. IBM, for example, has about 20 of them running; these are accessible via a cloud where various “use cases” (business cases on a small, experimental scale) are being trialled. IBM now has more than 460,000 registered users who have collectively implemented more than 2 trillion quantum circuits since 2016. These calculations do not yet offer a quantum advantage, however. They are also being used for scientific research, and this has generated some 1,750 scientific publications since 2016.[19]

Breakthroughs in terms of timesaving through quantum computing are probably going to be last to arrive. We should be aware, however, that in the long term the impact of quantum computing may well be the greatest, given the many optimisation and simulation applications that lie ahead.

18 Quantum.Amsterdam (n.d.).
19 Data provided by IBM.

Table 2 **Applications of quantum technology**

Application area	Promises	Examples
Computing	• greater computing power • solving complex mathematical problems • optimalisation • pattern recognition	• factorisation of large numbers, cracking encryption • pattern recognition in datasets • object recognition for self-driving cars • route optimisation for supply chain management • risk analysis in the financial sector • climate models
Simulation	• modelling natural processes	• simulating interactions in cells for disease control • modelling of biochemical processes, including for energy generation • (sustainable) materials development
Communication	• Safety • greater functionality	• quantum Internet (network of quantum computers) • Quantum Key Distribution (quantum cryptography)
Sensing	• precision measurement, higher resolution	• microscopy • seismology • gravity measurement • time measurement (atomic clocks) • navigation with and without GPS • research on dark matter

Source: Rathenau Instituut

3. Who is doing it? The Dutch innovation system

3.1. Funding from the Dutch government

National Agenda on Quantum Technology

The development of quantum technology is taking place in an international context. The Netherlands plays an important international role because of its advanced know-how in the quantum field. This is further stimulated via an ambitious investment programme. Since 2019, that programme has been steered by the National Agenda on Quantum Technology.[20] The National Agenda forms part of the Long-term Key Technologies Programme and was drawn up at the request of the Ministry of Economic Affairs and Climate Policy in cooperation with a number of knowledge institutions and businesses. Since 2020, €23.5 million has been made available for implementation of the agenda for a five-year period, with these funds going to existing quantum technology knowledge institutes such as QuTech (a partnership between TU Delft and TNO) and QuSoft (a partnership between the University of Amsterdam and the CWI research institute for mathematics and computer science).

The National Growth Fund

The funding provided so far is dwarfed by the €615 million allocated from the National Growth Fund to the Quantum Delta NL programme in mid-2021. Of this, 282 million has now been definitively allocated and 333 million earmarked “for a third phase” within an overall period of seven years. The Growth Fund investment is intended primarily to ensure that the Netherlands can establish a cutting-edge ecosystem in quantum technology, enabling technology development, business activity, and recruitment of talent and entrepreneurs. This is in keeping with the goal stated in 2019 of creating a “Silicon Valley” for quantum technology. The goal is to have an ecosystem after the seven-year boost, with sufficient economic and societal earning power to continue to grow without additional government support.

3.2. A national quantum ecosystem

Why an innovation ecosystem?

The term “ecosystem” is used to describe a network of parties working together within an organisational structure so as to achieve a particular goal. In the case of quantum technology, an ecosystem approach has been adopted as the innovation strategy because numerous parties need to cooperate to ensure that the technology both works and can be usefully applied. Both the hardware and the software consist of different components, with multiple parties being involved in developing them. Moreover, creating effective applications will in many cases require combining quantum technology with (related) technologies from other sectors.

Many different parties are therefore involved in developing quantum technology. The ecosystem approach is intended to ensure effective coordination between the different

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20 Quantum Delta Netherlands (2019).

types of knowledge and expertise, and also the needs of the cooperating parties. Besides the universities with their specialised institutes, both large companies and smaller suppliers and start-ups play a role. Talent development has also been provided for in the eco-system strategy and the ELSA approach has also been incorporated through the Quantum & Society action line, for which 20 million has been earmarked.[21]

Quantum Delta

The Growth Fund investment has been allocated to Quantum Delta. Quantum Delta can be seen as a single national ecosystem made up of five different clusters. One important hub is the Delft quantum cluster, with the QuTech research institute, the QuantumLab, the House of Quantum, and a number of affiliated enterprises. Quantum Delta's other four clusters are located at the University of Amsterdam, Leiden University, the University of Twente, and Eindhoven University of Technology.

Each of the five clusters has its own area of specialisation and can also be viewed separately as an ecosystem. Amsterdam, for example, focuses primarily on algorithm and application development together with end-users and with providers of qubit platforms. The networking organisation that brings parties together is called Quantum.Amsterdam. Besides the University of Amsterdam, the parties involved are CWI, TNO, the e-Science Centre, SURF (the collaborative organisation for IT in Dutch education and research), Quantum Inspire (with IBM), and QuiX (University of Twente).

Efforts

A great deal of money is going into scientific research.[22] Results are often not yet apparent in the form of usable applications. One excellent breakthrough has been the creation of a working photonic quantum computer by QuiX. Delft researchers' successful teleportation last year by means of entanglement is also important.[23] In this project QuTech has joined forces with private parties such as KPN and Eurofiber to create a network of nodes that can exchange entangled qubits.[24] The leading position of the Netherlands in quantum Internet development is also apparent from a major EU grant that was recently awarded for developing a secure communication infrastructure.[25]

3.3. International research funding

The EU coordinates its quantum programme through the Quantum Flagship, Horizon 2022 projects, and EuroQCI, which was set up specifically for quantum communication. The Netherlands has been successful in securing EU funding for quantum communication. The EU also encourages projects that extend beyond national borders.

21 ELSA stands for Ethical, Legal, and Social Aspects of Technology. An ELSA approach aims at socially responsible technological development and innovation.
22 It is perhaps not entirely correct to refer to this as fundamental (or pure) science, given that the research is taking place in the context of creating applications such as a quantum computer.
23 Henke (2022).
24 Monterie (2022), TU Delft (2019a), see also https://www.tudelft.nl/2019/tu-delft/kpn-en-qutech-slaan-handen-ineen-om-quantum-internet-te-realiseren. See also QuTech (n.d.).
25 Meijer (2022).

With that in mind, the Netherlands has announced a partnership with France and Germany.[26]

Many countries have an innovation agenda for quantum technology, which they link to public investment. A global overview shows that few countries invest more than the Netherlands.[27] Within the EU, those countries are only France and Germany, while the US, Canada, and the UK invest just over a billion dollars. Only China is investing more, namely roughly $15 billion. After China, the European Union is by far the biggest investor of public money, i.e. around $7 billion (total of investments by Member States). However private investment in Canada, the UK, and especially the US is much higher than in the EU and China. The Netherlands recently signed a declaration with the United States setting out their intention to increase cooperation and knowledge exchange.[28]

26 De la Rie (2022).
27 Qureca (2022), see also McKinsey & Company (2022).
28 U.S. Department of State (2023).

4. What do we need to watch out for? Public values

The new quantum technology has not permeated very far into society. Yet it already raises many societal questions. In this section, we discuss those societal questions by considering a number of public values. We have decided not to discuss the issues raised by quantum technology according to their area of application because computing is involved in all of them, and some of the issues affect all areas of application.

On the security front, there are various concerns regarding cyber security, protection of privacy, and military resources. Another issue is whether quantum technology will contribute to enhancing sustainability. There are also issues regarding justice, strategic autonomy, knowledge security, and safeguarding expertise. Some of the issues dealt with here, for example regarding surveillance, play an important role in artificial intelligence and the digital transition in general as well. The development of quantum technology may however intensify those issues.[29]

4.1. Security

Cyber security

The possibility of cracking the current encryption of online data traffic using quantum computers is perhaps the biggest concern regarding quantum technology. Enemy nations or criminals can then break into all kinds of systems containing classified information. This could greatly undermine political and economic stability.

This threat is not expected to become manifest until there are quantum computers made up of millions of physical qubits, and – as already noted – developing such computers will take up to 15 or 25 years. Nevertheless encrypted data can now already be stored to be decrypted and put to use later (“*harvest now, decrypt later*”). For real-time banking traffic, this is not very relevant, but it is relevant when sensitive information of governments and businesses is involved.[30] Moreover, the government is required by law to protect state secrets for 20 years, an obligation that it may no longer be able to meet.

Alternative security standards and protocols are therefore needed for current encryption by means of factorisation, which cannot be cracked by quantum computers. A number of alternatives are already in development. Alternatives developed with conventional computers are referred to as “post-quantum encryption”. However, quantum technology can also provide new standards *itself*, such as the *Quantum Key Distribution* (QKD), already referred to in part 2.

But if information encrypted with QKD can indeed no longer be cracked, another problem presents itself, namely that intelligence agencies or whistle-blowers will no longer be able to access it either. And if the Internet can no longer be tapped into, a

29 See white paper Quantum Delta Netherlands (2023a). The Exploratory Quantum Technology Assessment tool (Quantum Delta Netherlands 2023b) also relies heavily on the *Mission AI* advisory report by the Scientific Council for Government Policy (WRR 2021).

30 AIVD (2021).

vast and inaccessible "dark web" may be created where criminals can operate undisturbed. Where the current form of encryption is concerned, there is already debate about the extent to which the door to decryption should remain ajar; in the case of QKD, that issue becomes even more urgent.

Whether QKD is indeed hack-proof and can provide the same functionality as other forms of encryption is still uncertain. What is certain, however, is that the transition to a different method of encryption will be a huge logistical, cost-intensive and time-consuming operation, given that it requires setting up a new infrastructure. By comparison, replacing all bank cards – which will then also be necessary – is just a minor issue.

Privacy protection

The possibility of decryption also has implications for protecting privacy, because it could lead to personal data becoming public. Quantum computers can also erode privacy by making new connections between data sets through data analysis, and using those connections to categorise people. One important issue is whether quantum algorithms pose greater surveillance risks than current AI systems. There is concern that both governments and corporations will increase their control over citizens and consumers with quantum technology.[31]

That concern is also apparent with quantum sensing. The new sensors can measure more accurately and look into places that are currently hidden. For example, law enforcement agencies are already using infrared cameras to detect cannabis plantations without having to enter anywhere. With quantum sensing, still better opportunities for "looking inside" are expected to emerge.[32] The question is who will be permitted to do that and under which circumstances it would be desirable to do so. The new possibilities for sensing and computing challenge existing privacy boundaries. This demands that we think carefully about regulation of the new methods of observation and analysis using quantum technology.[33]

Military security

Finally, there are military security concerns.[34] Quantum technology is expected to make new biological weapons possible.[35] Rockets will be able to hit their target with greater precision due to faster computing, while more accurate measurement of gravity and electromagnetic fields means they are expected to be more responsive to their environment and thus more autonomous.[36]

31 Krishnamurthy (2022) p.4 and Quantum Delta Netherlands (2019) p.83.
32 UK National Quantum Technologies Programme (n.d.).
33 Bruno & Spano (2021). For overarching legal approaches to quantum technology see Van Daalen (2022), Krishnamurthy, V. (2022), Hoofnagle & Garfinkel (2021), and Kop, M (2021a).
34 Krelina (2021).
35 Quantum Delta Netherlands (2019) p.52.
36 Van Weerd & Lassche (2021) p. 13, Krelina (2021) p.2, Advesraad Internationale Vraagstukken (2021) pp. 20-21.

Sensing can further increase armies' arsenal, for example by making the underground cable infrastructure visible or by using gravitational sensors to track submarines armed with nuclear weapons where GPS signals are absent. Whether military quantum applications are an opportunity or a risk depends, among other things, on who gets their hands on these applications (first).

Both military applications and cyber security call for stepping up international diplomacy, with it being obvious that the Netherlands will act within the framework of the EU and NATO.[37] Making international agreements will be difficult, given rising geopolitical tensions. Another complicating factor is that the distinction between technological development and innovation for civil and military purposes is becoming increasingly blurred (*dual use*). A ban on a particular technology may therefore also prohibit desirable applications.[38] To prevent this, regulations will increasingly take the form of principles and standards for responsible use of technology, rather than a complete ban. However difficult it may be, it is necessary to strive for such international agreements for quantum technology.[39]

4.2. Sustainability

"Quantum computing saves the planet." Slogans such as this suggest that quantum technology will be decisive in the transition to a sustainable society. Because quantum computers compute faster, computation will consume less energy. Chemical materials research is expected to produce more efficient batteries and more efficient solar cells. Finally, quantum algorithms can help optimise all the energy consumption within electricity networks.

However, the net energy gain from quantum technology is not entirely clear. Quantum computers may well increase the number of calculations, which could in fact lead to higher energy consumption. Cooling superconducting computers to near absolute zero takes a great deal of energy. New post-quantum encryption techniques may also entail high power consumption.[40] Finally, constructing quantum computers – true, this also applies to other artefacts such as electric cars– requires scarce materials and extracting them may involve environmental damage. Whether quantum technology will contribute to a sustainable society is therefore still unknown. Be that as it may, it seems prudent to already make quantum technology part of an integrated vision of the digital infrastructure and the energy consumption associated with it.[41]

4.3. Justice

Intensifying data analysis using quantum technology amplifies current concerns regarding justice. As with AI systems, profiling with quantum technology can put equal treatment under pressure and facilitate discrimination. More specifically, the question

37 Reding et al. (2023) and Riekeles (2023).
38 Rathenau Instituut (2021b).
39 It is relevant in this context that the European Space Agency is a partner of EuroQCI. European Commission (z.d.6).
40 For research on this, see Roma, Tai & Hassan (2021), and Beckwith, Kaps & Gaj (n.d.).
41 Rathenau Instituut (2022b).

arises as to who will be able to benefit from the applications of quantum technology. There is concern that the "digital divide" – i.e. unequal access to digital resources – will extend into a "quantum divide". This concern is essentially about the fair distribution of well-being and power.[42]

Access to the first powerful quantum computers will almost certainly be very limited. In the case of conventional computers, widespread distribution – eventually into everyone's living room – has come about. Whether the same will happen with quantum computers is uncertain. Which parties will be the first to use quantum computers, and more importantly, what will they be used for? This leads into questions relating to our section (below) on strategic autonomy, because who will decide that? Will the ball be in the court of a few big technology companies once they own the first quantum computers? And if quantum computers become accessible via cloud services, won't the party controlling that access gain too much power?

Where cloud access is concerned, another problem has been voiced that works in the other direction, namely "blind computing". The party that executes the commands on the quantum computer may not know what is executed, because the client can conceal that using QKD. That party may therefore unwittingly cooperate in undesirable quantum applications.

More political and public debate on these issues is desirable so as to reveal the interests and values surrounding the development of quantum technology.[43] Preferably, government, businesses, science, civil-society organisations, and the public must all have a say in the use of quantum technology and how it is regulated.[44]

Because the transition to society has yet to take place, we are in a good starting position for already incorporating the societal impact of the new technology in an early stage of the development process. One important initiative in this regard is the Quantum & Society action line that forms part of Quantum Delta. Quantum & Society has 20 million euros to spend on researching the societal impact of quantum technology, disseminating knowledge, and linking that knowledge to mission-driven innovation.

4.4. Strategic autonomy

Quantum Delta is a partnership between public and private parties. A number of large foreign companies, such as IBM, Google and Microsoft, are involved. The interests of governments, scientists, and private parties do not always coincide. It is therefore important to make effective agreements, for example on cloud access or on the role of the interested parties when public values such as security and sustainability are at

42 Hidary & Sarkar (2023) and Ten Holter et al. (2022).
43 Seskir et al. (2023), De Jong (2022), and DiVincenzo (2017).
44 Specific applications will raise their own questions, for example the ethical issues that arise if quantum simulation can be used to optimise genetic engineering. For each application, there will also be sector-specific rules and quality standards at play that are currently already in place and that will continue to apply undiminished to quantum technology.

stake. In order to make agreements on mission-driven innovation, for example, requires public guidance.[45]

Effective arrangements should also involve ensuring a level playing field that allows start-ups sufficient scope to develop and market new products and services. The question remains whether the current regulation of intellectual property has desirable outcomes for society.[46]

In general, the question is whether the Netherlands isn't missing out on opportunities for marketing fundamental know-how. The Netherlands possesses know-how of the highest order in the field of post-quantum cryptography but it seems to be leaving the initiative for marketing this knowledge to other countries. The US National Institute of Standards and Technology (NIST) sets the tone for the development of new encryption standards; companies capitalising on them are based outside the Netherlands, for example PQshield (UK) and SandboxAQ (US).[47]

The development of quantum technology is a long-term matter. The incentive package from the National Growth Fund is perhaps large but it has a limited horizon. Whether Quantum Delta will be strong enough to operate without (government) funding after seven years is as yet unknown. In general, the question is whether institutions have sufficient absorption capacity to handle the allocation of large funding programmes and also whether, if successful, they will be able to sustain the developed knowledge infrastructure after funding ceases.[48]

4.5. Knowledge security

Scientific research thrives on international collaboration. However, a thorny problem is that sharing knowledge publicly becomes more sensitive – for both commercial and for security reasons – as practical applications draw closer. This dilemma already came up in the Dutch House of Representatives during a discussion of whether quantum technology should be classified as highly sensitive.[49] The Security Screening Investments, Mergers and Acquisitions Act (VIFO in Dutch) applies only to devices and products and *not* to scientific knowledge per se. It is not always possible, however, to draw a rigid line between pure knowledge and applied knowledge. Given everything we know about the expected applications, should all knowledge of quantum technology therefore be classified as highly sensitive? This is a tricky dilemma. If quantum technology were to be classified as highly sensitive, it would create heightened barriers

45 The World Economic Forum's "governance principles" are in line with the 17 Sustainable Development Goals: World Economic Forum (2022).
46 Kop (2021b). According to Kop, "first movers" (usually a few universities and large companies) can hold on to exploitation rights indefinitely by clever use of current IP regimes. This can lead to an undesirable concentration of market power.
47 Dutch organisations such as Eindhoven University of Technology and CWI have however been involved in the creation of winning protocols.
48 Rathenau Instituut (2022a).
49 Parliamentary Documents II [*Kamerstukken II*] (2022/2023).

to international cooperation on fundamental research and also for security policies. These barriers could well be counterproductive.[50]

The geopolitical situation forces us to think hard about knowledge security. The Netherlands advocates open science and plays a global pioneering role in that regard.[51] Within the open science movement, there is a realisation that openness can only exist if it is subject to certain conditions: privacy, security, and economic interests must be protected. Such conditions may also be relevant to quantum policies. In any case, it will remain a challenge to balance between, on the one hand, cooperating with other countries and parties and, on the other, safeguarding the special position of the Netherlands.

4.6. Trust: the role of experts

A final point concerns what is referred to as the "expertise gap". There are not too many people with an expert-level grasp of how quantum technology works. When its applications find their way into society, we will be highly dependent on that small group of people. That raises questions regarding trustworthiness, trust, and accountability. How trustworthy are quantum computers? What about the explicability of quantum algorithms? Who can assess whether the results of calculations are correct and communicate about them? Who is responsible for decisions made using quantum technology? What is the role of experts in this regard?

Quantum scientists are not always concerned with the practical applications for which their scientific findings may ultimately be used. Nevertheless, accessible texts on quantum technology are available to a wider audience.[52] A National Quantum Technology Course is also soon to be launched. Furthermore, tools have been developed such as Quantum Chess, which can be used to playfully learn about computing with quantum properties, and Qiskit, which allows someone to get started with quantum computing.

Many people do not yet know, however, what quantum technology is and what its impact can be. Greater awareness is needed within society, among citizens, businesses, and other organisations. Do businesses and organisations know the best way to respond to information security risks? And what do they need to consider if they wish to innovate in a socially responsible manner using quantum technology?[53]

Besides the expertise gap there is also a "talent gap", i.e. the fact that there are not enough qualified people to achieve the aims regarding quantum technology. It is difficult to find people who are well versed in relevant disciplines for quantum technology – for software development, for example, both in mathematics, computer science, and

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50 Van den Broek (2022).

51 See Dijkgraaf (2023) for the open science agreement recently signed by the Dutch Ministry of Education, Culture and Science and 15 knowledge institutions.

52 Like the National Agenda on Quantum Technology, Van der Starre et al. (2021) is also accessibly written.

53 It is good that useful manuals for businesses (and other organisations) have recently been released: Attema et al. (2023) and Quantum Delta Netherlands (2023b).

physics. Two master's degree programmes are currently being set up, at TU Delft in collaboration with Leiden University (starting in 2023) and at the University of Amsterdam (starting in 2024). These programmes are intended to help resolve the shortage of skilled workers.

Table 3 **Societal issues in quantum technology**

Public value	Societal concerns
Cyber security	Current online encryption can be cracked, challenging both political and economic stability; *Quantum Key Distribution* potentially makes the Internet impermeable; meaning also that intelligence agencies can therefore no longer access it.
Privacy protection	Decryption can make personal data public; Increased surveillance capabilities by governments and businesses; *Quantum sensing* allows viewing in places currently inaccessible.
Military security	Development of new biological weapons; Increased precision, for example of autonomous weapons; Expansion of observation methods by quantum sensors.
Justice	Intensifying concerns about profiling with AI; Increase in unfair distribution of power and wealth (“quantum divide”).
Strategic autonomy	Current intellectual property laws may lead to concentration of power; Dependence on big technology companies increases; Level playing field must be guaranteed; Mission-driven innovation does not happen of its own accord; The Netherlands may be missing out on opportunities for marketing fundamental knowledge.
Knowledge security	International knowledge sharing is necessary but can jeopardise security, privacy, and economic opportunities.
Trust: the role of experts	*Expertise gap*: increase in dependence on a very small group of experts; *Talent gap*: shortage of qualified professionals to achieve aims in the quantum field.
Sustainability	It is still uncertain whether quantum technology will reduce or increase energy consumption.

Source: Rathenau Instituut

5. How to proceed?

5.1. Beyond the hype

The potential impact of quantum technology on society is huge. Substantial economic interests are also involved, with the McKinsey consulting firm estimating that by 2035 $700 billion will be involved worldwide. But that point has not yet been reached. Although the first applications of the new quantum technology are breaking through, the technology is still in the development phase in many respects. The idea of quantum technology as a gamechanger does not fit in very well with this situation. This Rathenau Scan also shows that quantum advantage is only to be expected for specific applications. A complete paradigm shift in digital computing is unlikely. Moreover, a carefully considered judgement on the impact of quantum technology needs to take a serious number of societal issues into account.

Initially, quantum technology was surrounded by a hype, and that hype set people and resources in motion. A number of authors have since pointed out that overblown expectations of quantum technology also have negative consequences.[54]

First, an overly positive narrative obstructs the view on the challenges that remain in getting quantum technology up and running, especially quantum computing.

Second, the hype robs us of the scope for an informed dialogue on promising applications and societal risks. Conflicting values here necessitate difficult policy choices. Take, for example, the need to guarantee knowledge security and intellectual property as opposed to the need for knowledge exchange and international cooperation. Tensions may also arise with respect to one specific public value; quantum technology can have both positive and negative effects on sustainability, for example.

Third, the hype partly determines the investments made in quantum technology. Globally, businesses and governments together putting by far the most money into quantum computing.[55] That makes sense because quantum computing still requires a lot of fundamental research. Yet computing may only be the last of the three application areas to yield concrete applications. As regards marketing its expertise, shouldn't the Netherlands perhaps focus more on sensing and communication? Do we have a vision on which applications are most suited for the Dutch economy?

Fourth, an overwrought perspective on quantum technology encourages competitive behaviour and the international rat race to be the first with a quantum computer. To an extent, competition is inevitable, given that the academic world, the market economy, and the geopolitical context are all highly competitive in nature. That competition is obviously productive. However, a rat race in the development of quantum technology also amplifies the societal risks to security (including knowledge security), justice, and

54 Waters (2023), Sarma (2022), Ezratty (2022), Coenen (2022), Roberson (2021).
55 McKinsey & Company (2022). Note that investment in the Netherlands is more evenly distributed across the three application areas of computing, sensing, and communication through the three catalyst programmes (KAT 1-3).

strategic autonomy. Where possible and desirable, it is therefore best to seek cooperation.

5.2. Towards a multifarious quantum policy

Although the development of quantum technology still involves numerous uncertainties, pressing societal questions are emerging. Experts and policymakers are already fully aware of the security issues that quantum technology entails. However, quantum technology also affects public values such as justice, strategic autonomy, sustainability, and trust. Development of the technology simultaneously involves various policy areas. In all these areas, both political and public debate regarding the required choices that need to be made in order to develop quantum technology 2.0 in a socially responsible manner is both desirable and necessary.

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- Prof. ir. Deborah Nas, Technische Universiteit Delft;
- Prof. dr. Christian Schaffner, Universiteit van Amsterdam;
- Dr. Armand Stekelenburg, International Business Machines Cooperation (IBM);
- Dr. Pieter Vermaas, Technische Universiteit Delft.

Tools

- https://qiskit.org/
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