NATIONAL AGENDA FOR QUANTUM TECHNOLOGY

QDNL
QUANTUM DELTA NEDERLAND

NATIONAL AGENDA FOR
QUANTUM TECHNOLOGY

September 2019

Foreword

My name is Robbert Dijkgraaf. I'm a big fan of both science and the Netherlands, which this National Agenda for Quantum Technology brings together in an exciting way.

I often say that the future is already here: it's in our labs and in the heads of our scientists and engineers. And quantum technology is a key part of that future. As well as providing the basis for developing fantastic new devices and industries, quantum technology can enable us to resolve the big problems facing our society, such as climate change, health care and security.

All over the world people are investing in quantum technology, but here in the Netherlands we're privileged to host a number of fantastic initiatives. Outstanding, world-leading research institutes such as QuTech in Delft, QuSoft in Amsterdam and QT/e in Eindhoven, excellent research groups in Leiden, Nijmegen, Groningen, Twente and Utrecht, coordinating bodies such as TNO and StartupDelta, and a range of exciting industrial partnerships and startups.

Now is the time for putting all those pieces together, for taking up the gauntlet and for investing in new talent, new researchers, new infrastructure and industry – in other words, in the entire ecosystem. This document sets the agenda for working on breakthroughs in research and innovation, on the development of new applications and markets, on the competences required in fields such as systems engineering, and on the ethical, legal and social aspects of quantum technology. If we action that agenda, by 2030 we'll have a cool, exciting and new science, plus a new industry, and maybe new solutions for building a better world as well.

I therefore hope that you'll enjoy reading this National Agenda for Quantum Technology, and that you'll give it your support. Because we're going to need help realizing the initiatives and activities described, and help creating the envisaged Dutch Quantum Delta, QΔNL!

Robbert Dijkgraaf
Director and Leon Levy Professor, Institute for Advanced Study, Princeton

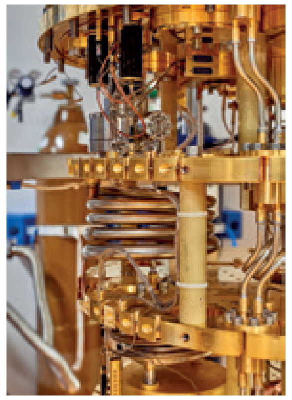
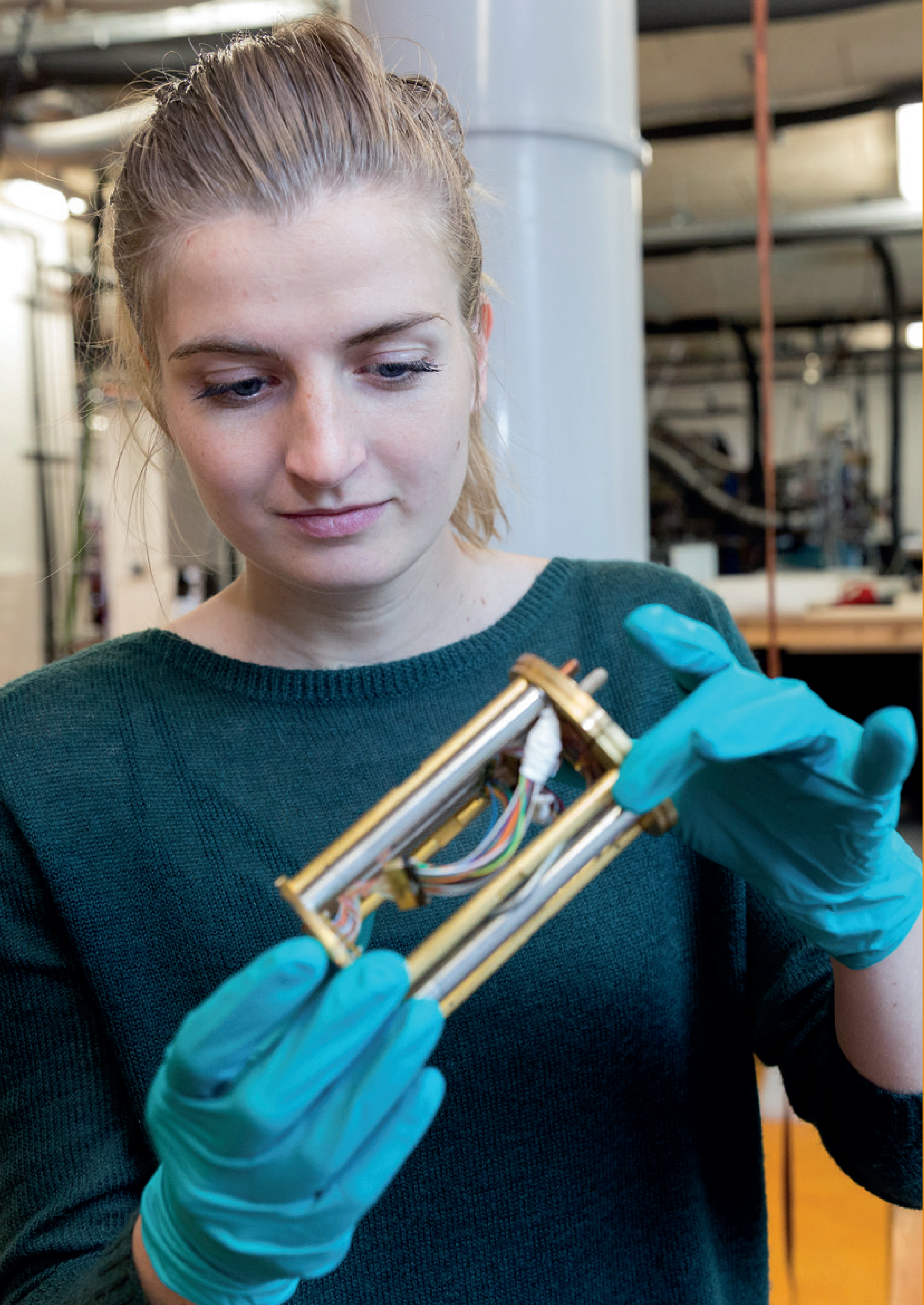


FOTO COVER
A highly sophisticated 'cryostat' cooling system, in which qubits are cooled to -273°C. Extremely low temperatures are required for qubits to retain a quantum state for long enough to enable them to be used for calculations.

Contents

Contents



Summary

Quantum technology is a key technology that enables radical new products and services. Quantum computers, quantum simulators, quantum networks and quantum sensors will soon be able to do things that 'classical' devices can't, such as perform molecular and materials calculations and enable geolocation without GPS. We are therefore at the dawn of a technological revolution, which is expected to make a major contribution to the resolution of social challenges in fields such as energy, food supply and health care. The Netherlands is in the scientific and technological vanguard of developments, and all around the world governments and corporations are investing heavily in quantum research and innovation.

The markets also have high expectations of quantum technology. Researchers predict that, over the next twenty years, the market for quantum technology will grow to more than 65 billion USD; by 2050 the global market is likely to be worth 300 billion USD. Parallels have been drawn with the semiconductor industry: quantum technology is at the stage of development that semiconductor technology was at in the 1950s. And the ultimate social and economic impact of quantum technology is potentially comparable to that of semiconductor technology, certainly when the effects of possible spinoffs to other fields are taken into account.

This National Agenda for Quantum Technology is intended to position the Netherlands as a world-leading centre and hub for quantum technology: the Quantum Delta NL, or QΔNL for short. We start from an excellent position: Dutch universities and knowledge institutions are at the cutting edge in the fields of qubits, quantum internet, quantum algorithms and post-quantum cryptography. They are consequently very attractive to commercial investors and talent from all parts of the world. We are also strong in systems engineering and in combining technologies to form operational systems: fields that are vital for innovation. The Netherlands intends to maintain and reinforce its pioneering role. Just as Silicon Valley was the driver and epicentre of semiconductor technology and its applications, the Netherlands aims to become the focal point for quantum technology. Ground breaking research, high-quality education, state-of-the-art facilities and programmes for bringing technology to market are required to attract talented people and dynamic businesses, and thus to generate a vigorous quantum ecosystem prominent on the European and global landscape.

Future agenda for QΔNL

Building mass and excellence in knowledge, talent, infrastructure and enterprise requires new investment and commitment. As well as the technology itself, the social acceptance and ethical aspects of quantum technology are also very important. This agenda sets out what needs to be done. Figure 1 visualizes the agenda's structure. Four sector-wide action lines have been defined: realization of research and innovation breakthroughs; ecosystem development, market creation and infrastructure; human capital; and starting social dialogue. The agenda additionally defines three ambitious unifying catalyst programmes (CAT programmes), designed to expedite the social and market introduction of quantum technology by utilizing demonstrator facilities that make the technology tangible and give end users and researchers the opportunity to gain experience with its use. The programmes also have a cohesive function, bringing together the four action lines, the ecosystem actors, and the scientific and user communities. A national help desk will be set up to guide anyone who wants to do something with quantum technology to appropriate parties in the Netherlands.

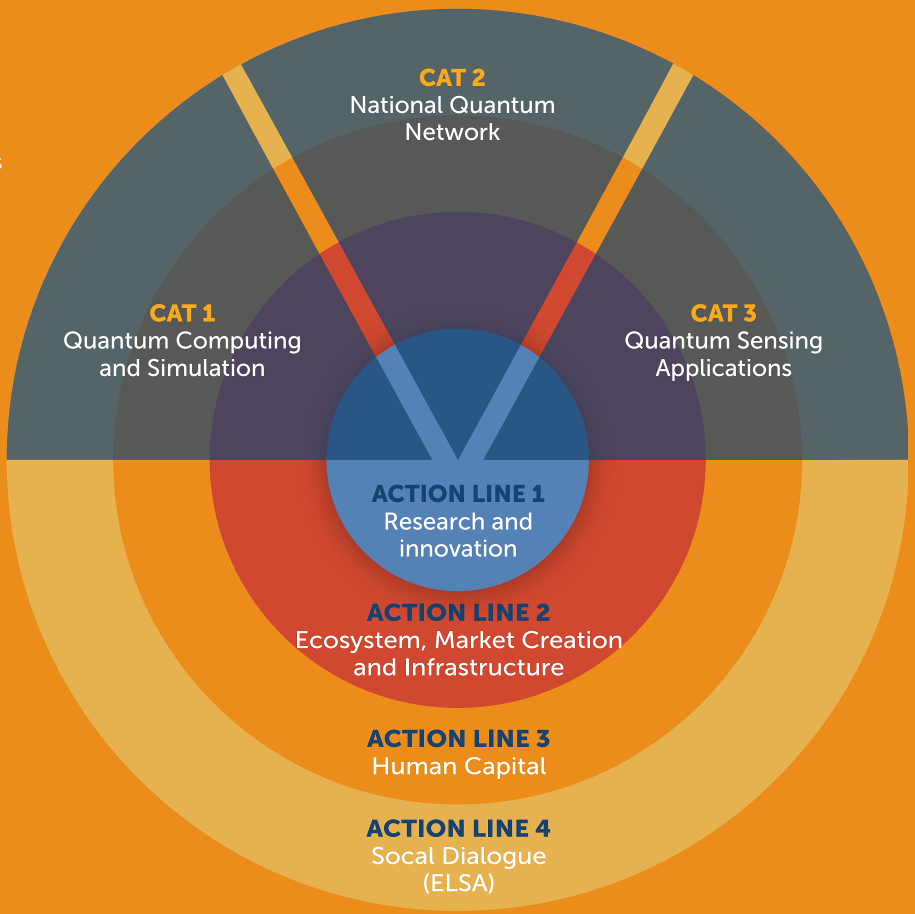
Three ambitious CAT programmes

CAT 1 | Quantum Computing and Simulation
To prepare society for quantum computers, quantum applications will be developed and demo versions made available online via the CAT project facilities. That will enable the government, the business community, technology developers and students to visit quantum computers, explore their capabilities and get experience with implementations on real hardware. The various facilities will connect knowledge institutions and enterprises working on quantum computing, at the national level and throughout the 'stack': from hardware to software and applications.

CAT 2 | National Quantum Network
With a view to taking quantum networks and the quantum internet to the next stage of development, a national quantum network will be created, interconnecting local knowledge clusters and opening the way for access by future users. The programme will enable both fundamental and applied research, and provides scope for hardware manufacturers to participate by developing infrastructure components. The open structure of the National Quantum Network will also facilitate the development of a vigorous software and security industry. Finally, the network will serve as a national testbed for data-intensive applications, such as cloud computing, the Internet of Things and autonomous driving.

CAT 3 | Quantum Sensing Applications
In order to further energize the development and application of quantum sensors, a multidisciplinary cooperation platform will be established, where researchers, systems engineers and developers can exchange experiences, share resources and partner with enterprises and end users in various sectors to define use cases and develop corresponding prototypes. A testing and user facility for quantum sensors will be realized as well, to assist enterprises and other organizations with innovation and the preparation of technologies for market. Ties will also be forged with related technologies, such as (integrated) photonics and electronics.

FIGURE 1
Four action lines and three ambitious unifying CAT programmes.



Four action lines

The National Agenda for Quantum Technology defines four action lines:

Action line 1 | Realization of research and innovation breakthroughs in six fields:
- Quantum computing
- Quantum simulation
- Quantum communication
- Quantum sensing
- Quantum algorithms
- Post-quantum cryptography

Action line 2 | Ecosystem development, market creation and infrastructure
1. International positioning of QΔNL and international embedding of the agenda
2. Creation of field labs as practical innovation environments
3. Extension of the required cleanroom facilities
4. Further development of the Delft quantum cluster for the Dutch ecosystem
5. Expansion and reinforcement of local centres within the national landscape
6. Establishment of a technology transfer programme; support for startups

Action line 3 | Human capital: education, knowledge and skills
7. Reinforcement of education, collaboration and knowledge exchange
8. Attraction and retention of talent from the Netherlands and other countries
9. Community building, conferences, summer schools and student exchanges

Action line 4 | Promotion of social dialogue regarding quantum technology
10. Initiation of (international) dialogue regarding quantum technology
11. Formation of a national ELSA Committee and professorship
12. Development of legal and ethical frameworks for quantum technology

Funding and organization

The total annual cost of the programme, including programmes already in progress, is estimated 102 million euros per year, of which 69 million is covered by current programmes. The new action lines will require the investment of 34 million per year. This Agenda is the collaborative product of a core team of people with diverse backgrounds but a shared goal. Numerous members of the 'golden triangle' were involved through various channels, including a well-attended national open day in April 2019 and a consultation group made up of about fifty representatives of the scientific, business and governmental communities. Operating as a coalition, the core team is willing to oversee implementation of the agenda, and intends to apply itself to that task energetically.

Urgency is required

Implementation of this agenda should not be delayed. The rest of the world is not standing still: other countries are investing heavily, and a fierce battle for brains is already being fought. Moreover, the technology is strategically important to our sovereignty. If the Netherlands is to retain a leading position, progress must be made quickly. Funds must be made available, and strategic priorities must be identified and addressed. The reason being that the development of quantum technology is necessarily an international phenomenon: no single country can develop the technology alone, but many countries are striving to maximize the proportion of the development effort that takes place within their borders. The Netherlands' interests are best served by pursuing an optimized balance between national strength and international cooperation, as successfully realized in the water sector and, by means of the Brainport region, in the semiconductor industry. The excellent position we already enjoy in quantum technology means that we have an outstanding opportunity of replicating those successes.

> ‘We are now witnessing the dawn of a second quantum revolution. These are therefore exciting times.’

01

A NATIONAL AGENDA FOR **QUANTUM TECHNOLOGY**

1.1 The potential of quantum technology

Quantum technology is a hot topic around the world. Following the first quantum revolution in the twentieth century, which gave us inventions such as the transistor and the laser, and thus led to today's computer and internet-based information society, we are now at the dawn of a second quantum revolution. These are therefore exciting times, because the second wave of quantum technology will enable things that can't be done with ‘classical’ devices. For example, quantum computers will have the potential to solve certain problems much more quickly than could ever be achieved using conventional computers, while quantum simulation will open the way to understanding quantum processes, such as the complex behaviour of molecules. With quantum communication, certain distributed problems can be resolved more efficiently and the security of information exchange can be enhanced by making message interception almost impossible – if anyone were to try, it would be immediately apparent to the sender and the recipient. Meanwhile, quantum sensors will be capable of performing precise measurements on a very small scale, in ways impossible for conventional sensors.

Quantum technology is ‘simply’ technology based on the principles of quantum mechanics, our most tested and precise theory of the world. Nevertheless, quantum technology is perceived as mysterious – almost magical – by many people. "If you think you understand quantum mechanics, you don't understand quantum mechanics", the famous physicist Richard Feynman once said. However, it is clear from various major breakthroughs made over the last decade that the principles can be applied in ground-breaking new technologies. For the upcoming generations of quantum technicians now being trained, quantum mechanics will become a practical discipline. The radical new applications enabled by the second quantum revolution will create promising opportunities for manufacturers and can help with the resolution of some of the great challenges facing society in fields such as energy, food supply and health care. Not surprisingly, therefore, governments and corporations around the globe are investing heavily in quantum technology. Although that investment is already yielding the first commercial applications, the potential of this field remains almost entirely untapped.

Once we master quantum technology, it will transform our world. When announcing that the 2012 Nobel Prize for Physics was awarded to Serge Haroche and David Wineland, the Nobel Committee said: "Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century." An attractive prospect, particularly considering that investment in the development of quantum computers, quantum networks, quantum simulators and quantum sensors will undoubtedly have spinoffs in other fields. Parallels may be drawn between the push for quantum technology and the space programme: the mission to put a man on the moon led to the development of new lightweight materials, medical devices, shock-absorbing footwear and countless other spinoffs.[1]

[1] *See: https://www.nasa.gov/sites/default/files/80660main_ApolloFS.pdf*

In short, quantum technology has huge potential for science, industry and society as a whole. This agenda sets out opportunities, time lines and initiatives for the realization of that potential.

1.2 Development of Quantum Delta NL

The Netherlands has an outstanding starting position and is therefore ideally placed to utilize the opportunities offered by quantum technology. Dutch universities and knowledge institutions are at the forefront of the global push to develop quantum hardware and software, as well as the associated control systems, algorithms and applications. We are one of the world's leading nations in the fields of qubits, quantum internet, quantum algorithms and post-quantum cryptography. A study by Elsevier[2] found, for example, that Dutch publications on quantum communication, quantum computing and encryption technologies had citation impact scores of between 1.6 and 2.1 - the best in Europe and far above the global average of 1.0. Citation impact is an indicator of the influence of research, and such high scores are clear evidence that some outstanding research is being done in our country. The Delft QuTech, National Icon since 2014, is a joint TUD/TNO knowledge institute with a unique global position, as recently confirmed by the excellent scores and feedback in an international evaluation undertaken under Robbert Dijkgraaf's leadership.[3] Other strong joint ventures are also making their mark, including QuSoft in Amsterdam and QT/e in Eindhoven. All those Dutch-based institutes are working closely with universities, startups and established enterprises, such as Microsoft, Intel, ABN AMRO, Delft Circuits, Qblox, Bosch and Shell. In February 2019, for example, King Willem-Alexander opened the Microsoft Quantum Lab on the campus of Delft University of Technology.

The Netherlands intends to maintain and reinforce its pioneering role. The players active within the Dutch ecosystem therefore aim to transform the Netherlands into a world-leading centre and hub for quantum technology: the Quantum Delta NL, or QΔNL for short. And now is the time to turn that ambition into reality. Quantum technology is currently at a stage of development comparable to that of transistor technology in the 1950s, and everyone knows what an enormous industry emerged from those beginnings. Just as Silicon Valley was the driver and epicentre of semi-conductor technology and its applications, the Netherlands wants to become the focal point for quantum technology. Groundbreaking research, high-quality education, state-of-the-art facilities for developing and testing the technology and new applications are required to attract talented people and dynamic businesses, and thus to generate a vigorous quantum ecosystem in the Netherlands.

Building mass and excellence in knowledge, talent, infrastructure and enterprise requires new investment and commitment. Consideration needs to be given not only to the technology itself, but also to the social acceptance and ethical aspects of quantum technology. This agenda provides the starting point for securing those goals; it is intended to set a flywheel in motion, as illustrated in Figure 2. For evidence that a flywheel effect can be achieved in the Netherlands, we need look no further than the ICT sector. By investing early in the development of internet technology, our country has secured a strong position on the international ICT stage. And the rewards have been considerable, with the Amsterdam Internet Exchange (AMS-IX) now one of the world's biggest internet hubs, major data centres coming to the country and the emergence of Dutch-based global players such as Adyen Payments and Booking.com. With this agenda, we want to pave the way for the Netherlands to play a similar role in the field of quantum technology.

1.3 Formulation of this agenda

In spring 2019, at the request of the State Secretary for Economic Affairs and Climate Policy and the high-tech systems and materials and ICT top sectors, Dutch knowledge institutions and enterprises set out to describe what was required for the realization of their ambitions for quantum technology. TNO, QuTech, QuSoft, EZK, the Dutch Research Council (NWO), QT/e and the Lorentz Institute linked up with AMS-IX, StartupDelta (Techleap.nl) and Microsoft to accept the challenge as part of the KIA/KIC process and the Multi-year Programmes for Key Technologies, in close consultation with the whole field. Numerous players in the 'golden triangle' were involved in the formulation of this agenda, providing input through, for example, a well-attended national open day and a broad-based consultation group, whose members included representatives of the Dutch Ministry of Defence and Ministry of the Interior and Kingdom Relations. This National Agenda for Quantum Technology is the product of that process.

The importance of quantum technology is recognized by the Dutch and European governments, both of which have designated quantum technology as a key technology. Policy proposals and guidelines have been set out, for example, in the European Quantum Flagship[4], the Quantum Manifesto[5] and Quantum Software Manifesto (2017), and the Dutch government's letter to parliament on 13 July 2018, headed 'Towards a Mission-driven Innovation Policy with Impact'[6]. In the mission-driven innovation policy, the emphasis is on the economic opportunities associated with social challenges and key technologies. Four central themes are identified: agriculture, water and food supply; health and social care; energy transition and durability; and security. The key technologies form a fifth theme; quantum technology is identified as one of the eight clusters of key technologies. That policy was taken as the starting point for this agenda.

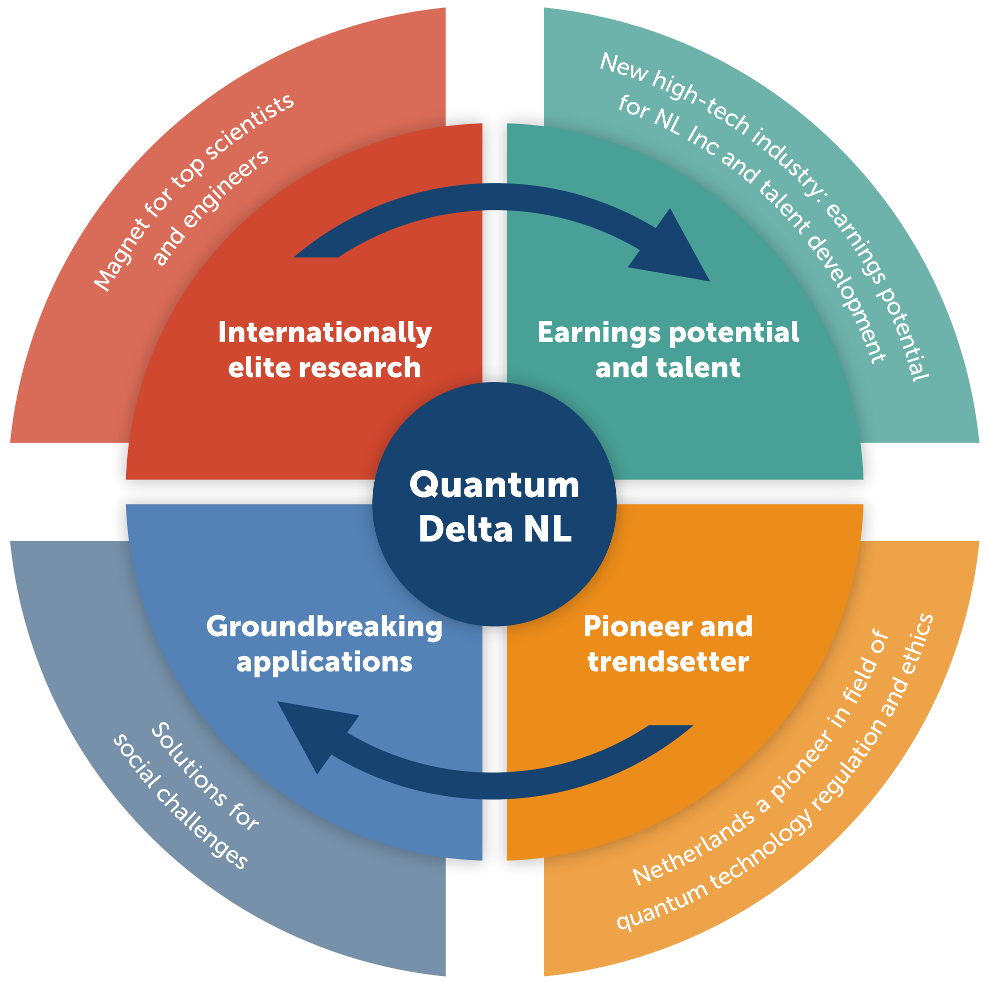


FIGURE 2
The Netherlands' ambition to develop a world-leading centre and hub for quantum technology: the **Quantum Delta NL**. The four quadrants reflect the scope of that ambition, while the arrows at the centre symbolize the interaction between the four fields. They also emphasize the purpose of this national agenda: to act as a flywheel for the development and application of quantum technology in the Netherlands.

[2] *Elsevier, 'Kwantitatieve analyse van onderzoek en innovatie in sleuteltechnologieën in Nederland', June 2018.*
[3] *See: https://www.qanu.nl/sites/default/files/inline-files/QANU%20Report%20Mid-Term%20Review%20QuTech%202015-2018_def.pdf*
[4] *See: https://qt.eu/*
[5] *Quantum Manifesto: A New Era of Technology, May 2016.*
[6] *Parliamentary document 33 009 (2017-2018), no. 63.*

1.4
Urgent action required

Implementation of this agenda should not be delayed. Other countries are not standing still; they are investing heavily in quantum technology. China and the USA have announced plans to put billions of dollars into the field, and other European countries have not been idle. Germany, for example, plans to invest 650 million euros, the UK has committed to following up its first National Quantum Technologies Programme and Sweden, although much smaller, has promised 100 million euros for quantum technology. The European Union has set aside a billion euros to fund its Quantum Technologies Flagship and taken the first steps towards creating a European quantum communication infrastructure; Dutch parties are involved in both initiatives.

If the Netherlands is to retain a leading position, the country needs to act quickly and to invest independently. As well as making funds available, strategic priorities must be identified and addressed. The reasons for doing so include the protection of our sovereignty. Quantum technology has strategic value. If the Netherlands and Europe do not wish to be dependent on the United States and China, it is imperative that we invest in this field. The Netherlands must use its resources intelligently and effectively, and we must align our activities with those of fellow EU and NATO countries. While China has centralized government control and corporations take the lead in the United States, the European approach is based on close, multidisciplinary collaboration between the government and the scientific and business communities. That approach has a strong tradition in the Netherlands, as evidenced by the formulation of this agenda. We excel at collaborative development, realization and application. And we can use that capability to our advantage.

1.5
Structure of the agenda

The structure of the National Agenda for Quantum Technology is as follows: following the introductory **Section 1**, a number of key principles of quantum technology are outlined in **Section 2** and translated into the four most promising application areas. Section 2 also includes a summary of current scientific and technological challenges. **Section 3** deals with the social and economic impact of quantum technology. The technology's potential for resolving social issues and driving the Dutch economy are sketched in relation to the four missions and various economic sectors. The ethical, legal and social implications of quantum technology's application are also considered.

Section 4 describes the Dutch quantum landscape from an international perspective, taking in research, education and commerce. The point is made that, in science, education and public-private collaboration, the Netherlands plays a leading role, as illustrated by the many examples presented in the inset boxes. The international cooperation necessary for realization of this agenda's ambitions is covered as well.

Building on Sections 3 and 4, **Section 5** explains what needs to be done to take advantage of the identified opportunities and to make the Netherlands a world-leading centre for quantum technology. The activities are divided across four action lines:

Action line 1
Realization of research and innovation breakthroughs;

Action line 2
Ecosystem development, market creation and infrastructure;

Action line 3
Human capital: education, knowledge and skills;

Action line 4
Starting social dialogue about quantum technology.

The agenda additionally defines three cutting-edge catalyst programmes (CAT programmes), whose purpose will be to demonstrate developments in quantum technology so that they become tangible, and to accelerate their social and industrial adoption. The CATs represent acceleration and interconnection: they cover the agenda's four action lines, bring together the various players active in the ecosystem, combine hardware and software, and connect science and research with use cases and applications. The three CAT programmes are:

CAT 1
Quantum Computing and Simulation

CAT 2
National Quantum Network

CAT 3
Quantum Sensing Applications

The criteria for implementation and realization of the agenda are set out in **Section 6**. The organization, governance and funding of the agenda's implementation are also considered.

'Quantum technology enables things that are not possible with classical technology.'

02

WHAT MAKES **QUANTUM TECHNOLOGY** SO SPECIAL?

2.1 The key principles of quantum technology

Quantum mechanics dates back to the early twentieth century, when experimental results began to emerge, which could not be explained using the established scientific theories of the day. A new theory was accordingly developed by leading European physicists, such as Einstein, Bohr, Schrödinger and Heisenberg. That 'quantum theory' explains the behaviour of energy and matter at the atomic and subatomic scales: the world of the very smallest 'quantum particles'. Numerous Dutch physicists, including the Nobel Prize winners Kamerlingh Onnes, Lorentz and Zeeman, made important contributions to quantum theory. The behaviour of quantum particles forms the basis for the working of quantum computers, quantum communication systems, quantum sensors and quantum simulators, as explained in subsection 2.2. To aid understanding of that topic, two key principles of quantum mechanics are first considered: entanglement and superposition. To a large extent, it is the application of those two principles that underpins the second quantum revolution.

2.1.1 Entanglement

Entanglement is a phenomenon that occurs when two or more quantum particles (e.g. photons or electrons) enter a state that cannot be described exclusively by the states of the individual particles; the particles form a unified system, as it were. If two particles are entangled, measuring the state of the one particle instantly yields information about the state of the other, even if the two particles are not close together. It is as if they are communicating and exchanging information instantaneously, i.e. faster than the speed of light. However, that is not the case. It is something that we humans cannot actually comprehend. Although Einstein was consequently dismissive of this "spooky action at a distance", it has since been demonstrated experimentally that entanglement is a real phenomenon. In 2015, an experiment was performed at QuTech in Delft, conclusively showing for the first time that entanglement can remain effective even at distance.[7]

2.1.2 Superposition

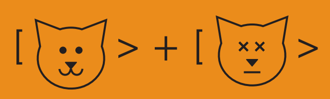
A quantum particle can be in multiple states simultaneously. For example, the rotation of an electron in a magnetic field can be a random combination of 'upward' and 'downward', until we measure it and identify a single direction of movement. That is in contrast to a coin, which we know is either heads up or tails up; it is not in a combined state (both heads up and tails up) until we look at it. That principle of quantum mechanics is known as superposition, and it too is beyond human comprehension.

[7] *'Loophole-free bell inequality violation using electron spins separated by 1.3 kilometres', Hensen, B. et al., Nature 526 (2015).*

Entanglement and superposition are illustrated in the inset box by reference to Schrödinger's cat.[8] In the illustration, cats symbolize the states of microscopic quantum systems (made up of, for example, photons or electrons). In macroscopic systems (such as real cats) the phenomena are not observable; they 'average out' as it were.

Schrödinger's cat: superposition and entanglement

Superposition

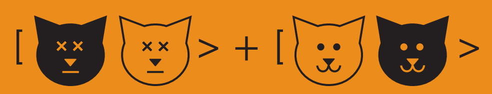


This is a white cat in a state of superposition: its state is simultaneously 'dead' and 'alive'. (The plus sign (+) indicates a state of superposition; the brackets ([>) indicate the individual simultaneous states, known as 'eigenstates'.) As soon as you look at the cat (perform a measurement), you observe that it is either dead or alive: the superposition 'collapses' to leave a single eigenstate.

Distinct superpositions without entanglement

Here we have two cats: one white and one black. Each is separately in a state of superposition, being both dead and alive. If you look at the white cat and thus determine its state, you learn nothing about the state of the black cat. The cats are therefore not entangled.

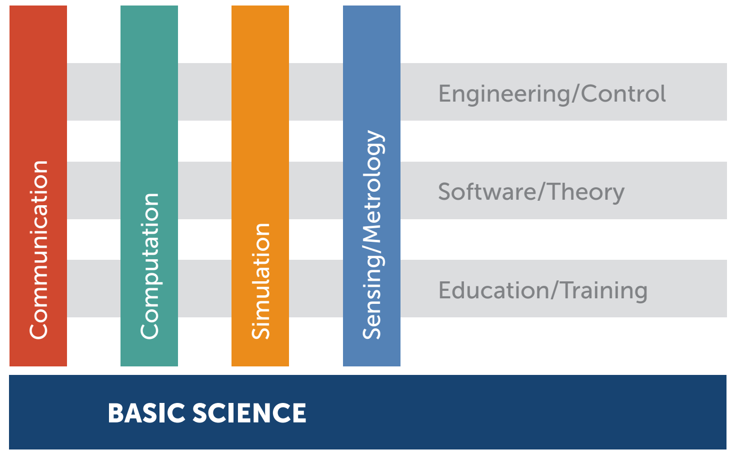
Two entangled cats



Again, we have two cats: one white and one black. Their combined state is a superposition of the states 'both cats are dead' and 'both cats are alive'. If you look at the white cat and thus determine that it is dead, the state of the black cat instantly becomes 'dead' as well. If you observe that the white cat is alive, the black cat instantly becomes 'alive' as well, even if it is far removed from the white one. That is called entanglement.

[8] *In the 1930s, the famous Austrian physicist Erwin Schrödinger carried out a thought experiment with a cat, which has since attracted so much attention that it is now known simply as 'Schrödinger's cat'.*

FIGURE 3
Structure of the European Quantum Flagship.



2.2 Four promising application areas

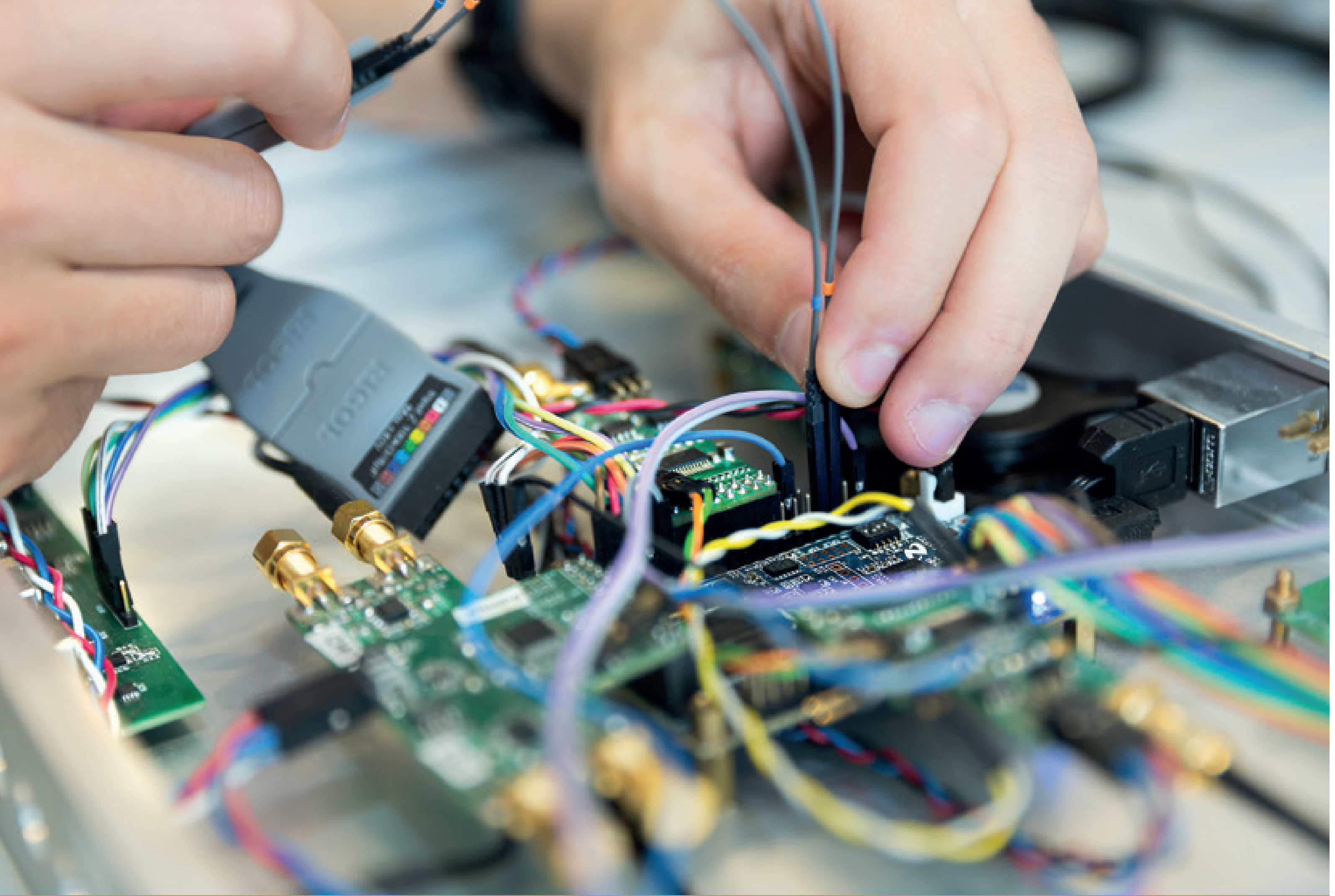
In the context of this agenda, quantum technology is divided into four major application areas matching the European Quantum Flagship: quantum computation, quantum communication, quantum simulation, and quantum sensing and metrology. The Quantum Flagship also defines three work fields, which are relevant to all four pillars: engineering and control, software and theory, and education and training. Underpinning the entire structure is what the Flagship refers to as 'basic science'. The structure of the Quantum Flagship is illustrated in Figure 3.

2.2.1 Universal quantum computers

Quantum computers make intelligent use of quantum mechanical effects, with superposition and entanglement playing important roles. As a result, they work in a fundamentally different way from classical computers. A classical computer calculates using bits, each of which can have value of 0 or 1. A quantum computer uses qubits (a contraction of 'quantum bits'), whose value can simultaneously be both 0 and 1. In other words, a qubit can be in a superposition of 0 and 1. The qubits in a quantum computer can collectively be in a superposition of all possible states. By getting the computer to perform operations on the qubits, it is in principle possible to perform multiple calculations at the same time, as described in the inset text comparing the quantum computer and the classical computer.

Because they can perform multiple operations simultaneously, quantum computers can potentially solve problems that are practically impossible for classical computers, due to the exponentially increasing disparity in the time required. Quantum computers will not replace classical computers, but could enable certain calculations that require more computing power than classical computers are ever likely to possess. That opens the way for revolutionary applications, such as the resolution of complex optimization challenges, or the prediction, simulation and modelling of the behaviour of molecules, catalysts and new materials. Universal quantum computers are digital machines based on 'gates'. Like classical computers, they can be repeatedly reprogrammed to solve new problems.

Progress in the field of quantum hardware has been such that quantum computers are likely to become available for certain applications within a few years. Just as a classical computer is unusable without appropriate software, a quantum computer is of no value unless good quantum software is also available. Both quantum hardware and quantum software are therefore essential for realizing the promise of quantum computing.



Quantum computer and classical computer compared

A classical computer performs operations on bits, each of which has a value of 0 or 1. Suppose that we use a classical computer to perform a calculation with a bit whose value is 0. In order to make the same calculation with a bit whose value is 1, the classical computer has to perform a completely separate operation. However, a quantum computer performing the same operation on a qubit (whose value is a superposition 0 and 1) will simultaneously get the result associated with a bit value of 0 and that associated with a bit value of 1, in superposition. In other words, while the classical computer needs to perform two separate operations, the quantum computer can obtain the same outcome with a single operation. The advantage of doing so increases exponentially as the number of qubits used rises: whereas a classical computer can perform n operations with n bits, the quantum computer can in principle perform 2^n simultaneous operations with n qubits. Thus, a quantum computer can in principle calculate 2^n times as fast as a classical computer. However, there's a catch.

As soon as a calculation is performed and the values of the qubits are read, the state of superposition collapses and all the qubits take on a single value. Consequently, a quantum computer is not 'merely' a very fast computer that performs parallel calculations. The measured value must of course represent the correct result. And, in that context, interference[9] and software are influential. Quantum algorithms must ensure that we end up with the 'right' answer (by means of constructive interference) and that 'wrong' answers are extinguished (destructive interference). Writing quantum software is therefore fundamentally different from writing classical software: quantum software often uses entirely new and frequently counterintuitive ideas.

[9] *In quantum mechanics, a particle can also be described as a matter wave: it simultaneously has the properties of a particle and those of a wave. The phenomenon is known as wave-particle duality. Wave phenomena are subject to interference, whose effect may be amplification ('constructive interference') or extinction ('destructive interference') of the wave.*

The quantum computing stack

Both quantum hardware and quantum software are essential for realizing the promise of quantum computing. The average user of a classical computer experiences software on a level that is far removed from the machine's individual transistors: between the user and the chip are innumerable algorithms, which ensure that a mouse click generates a sequence of nanometre-scale electronic signals, resulting in, for example, an e-mail being opened.

Quantum machines have a similar layered structure, as illustrated in the figure[10]. The quantum computing stack is made up of multiple 'layers': from interaction with the outside world via algorithms and software to the hardware's control over individual qubits on the quantum chip. Just as a quantum computer or quantum simulator has a stack of the kind illustrated, a quantum network (where commands to entangle particles or read a quantum state are given at the machine level, while the user seeks access to certain data via a web interface) has a software stack. Similarly, multiple hardware and software layers are required to enable quantum sensors to be used and read. The complexity of a sensor stack depends on the application (e.g. a network of quantum sensors in an aircraft for navigation purposes, with the pilot or autopilot making course-adjustment decisions at the highest level).

In order to realize applications and end use cases, it will be necessary to develop quantum algorithms and quantum applications. Both platform-agnostic development in the upper stack layers and the development of hardware-specific quantum algorithms and quantum applications are envisaged. Moreover, the development of new quantum hardware in the lower stack layers will drive continuous innovation in the layers above. Ultimately, the two development pathways will need to be integrated in the interests of coherent innovation.

2.2.2 Quantum simulators

While a universal quantum computer can be continually reprogrammed to solve new and distinct problems, a quantum simulator is actually a quantum computer that (to date) usually has a single specific application or purpose; it is a special-purpose quantum computer. For example, quantum simulators are being built that can model specific molecular interactions or resolve specific optimization problems. Quantum simulators also play an important role in the compilation and optimization of quantum software protocols ('quantum code'). The concept of the quantum simulator can be traced back directly to Richard Feynman's suggestion in 1982 that it would be much better to address difficult quantum mechanical problems using another quantum system than using a classical computer. The success of that approach would depend, however, on the quantum system in question being built and manipulated under highly controlled conditions. Such quantum simulators can serve as tools for resolving multi-particle problems in solid matter physics, quantum chemistry, materials science and high-energy physics. That ability is based on the utilization of quantum mechanical phenomena – a quantum simulator is, after all, by definition a quantum system.

There are various ways of creating quantum simulators, including the application of extremely cold atoms, electrons with polarized photons and electrons arranged in artificial grids. Quantum mechanical interactions (involving

[10] *Illustration: Koen Bertels, 'A full system architecture', presented during a workshop at the International Conference on Parallel Processing (ICPP), Oregon USA, 13 August 2018.*

superposition or entanglement) among the atoms, electrons or photons enable such systems to model other complex quantum systems.

For calculation purposes, a specialist quantum device can also be used as a quantum coprocessor, in tandem with a classical computer. Such a set-up is referred to as a hybrid quantum simulator. A hybrid simulator features a mathematical 'loop' via the quantum coprocessor that enables the performance of complex calculations, which would be practically impossible using classical processors only. Experimental results have already been achieved, including the quantum simulation of a complex quantum electrodynamic calculation described in the inset text.

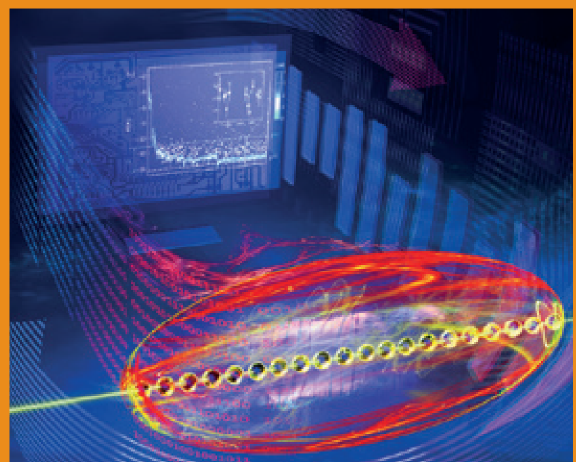
2.2.3 Quantum communication

In quantum communication, the principle of entanglement plays an important role. Qubits can be entangled with one another, enabling the quantum states of various particles to be correlated across great distances. Another property of qubits is that they cannot be copied with intact superposition. Consequently, any attempt to intercept, read and forward a qubit-based communication is detectable by comparing the states of the received qubits with the states of the sent qubits. Quantum communication is therefore potentially immune to outside interference, providing that the sending and receiving parties can reliably identify one another. That opens the way for data to be exchanged and processed in a fundamentally secure manner. However, the long-distance transmission of qubits is not straightforward. To address that problem, efforts are being made to develop special 'quantum repeaters'.

In due course, the various quantum communication networks are expected to evolve into a global 'quantum internet', enabling secure communication, secure online applications and secure position verification. Other possible applications include the synchronization of atomic clocks and the creation of a large quantum computing network by interconnecting geographically dispersed quantum computers. By harnessing entanglement, such a network could open the way for calculations to be performed on remote quantum computers without risking unauthorized data interception. A quantum internet would also enable the interconnection of telescopes around the world to act as a single giant telescope capable of looking deeper into space than ever before.

A hybrid quantum simulator with twenty ions checks its own answers

A research team in Innsbruck (including a former Eindhoven doctoral student) has used a programmable quantum simulator with twenty ions as a coprocessor to perform quantum mechanical calculations that require more computing power than classical processors can deliver[11]. The hybrid quantum simulator was able to solve a quantum electrodynamic modelling problem, which had previously been possible only using a digital quantum simulator with 220 gates. Thanks to the development of smart algorithms, the hybrid simulator was even able to verify its own results. (Image: University of Innsbruck, all copyrights reserved.)



[11] *Self-verifying variational quantum simulation of lattice models', C. Kokail et al. Nature 569 (2019).*

Figure 4, from a recent vision paper in Science, shows the various development stages of a quantum internet and some of its possible applications. We are currently at the very start of this exciting development process (the 'Trusted repeater' level).

Scientists based at various places in the Netherlands and elsewhere are busy creating quantum networks. The expectation is that the first rudimentary networks capable of testing the principles and functionalities involved in the first four stages of quantum internet development (up to and including the 'Quantum memory' stage in Figure 4) will be created in the next few years. The Netherlands is currently at the forefront of efforts to create such a network based on fibre-optic links; we also have an excellent classical network knowledge base thanks to the AMS-IX and other facilities. Our country is therefore ideally placed to play a major role in the establishment and development of a global quantum internet industry.

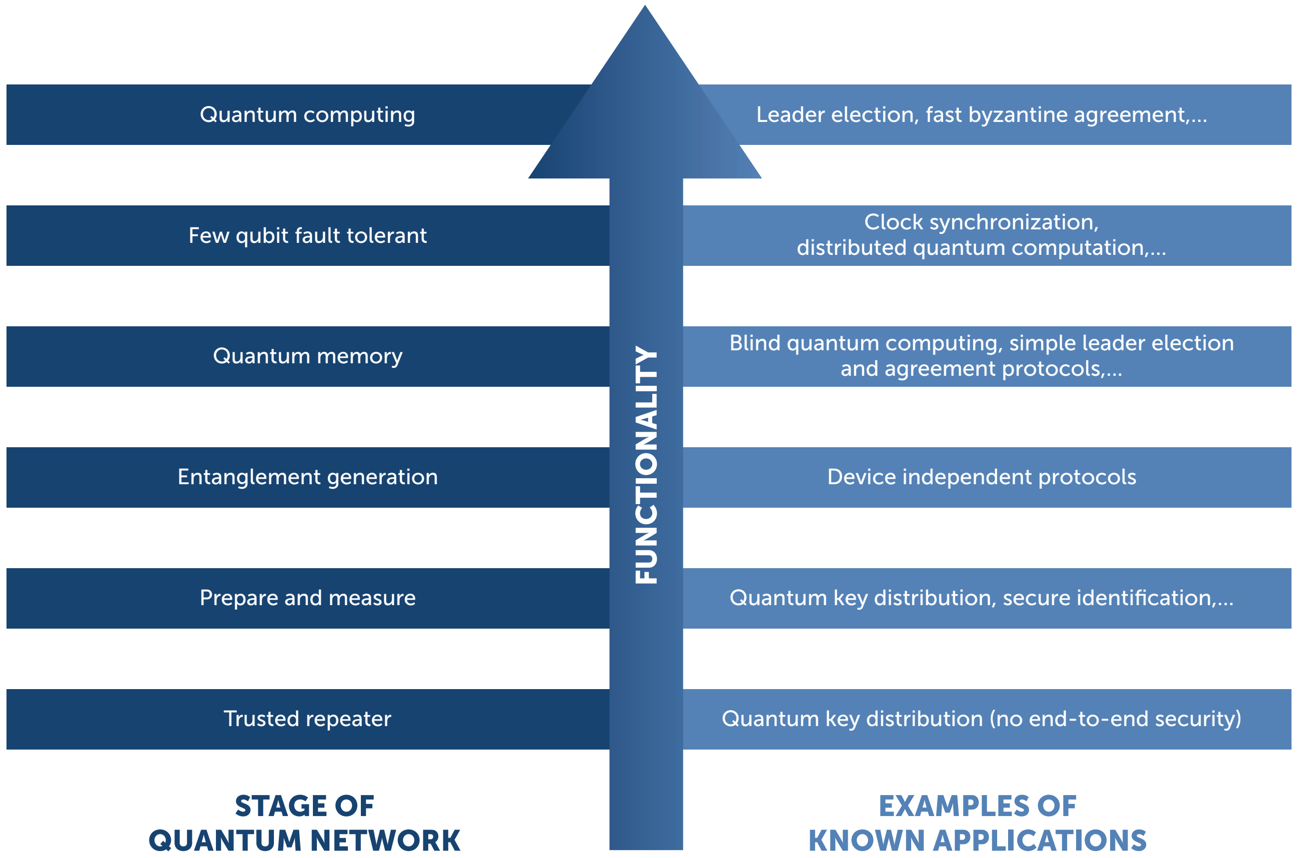


FIGURE 4
The stages of quantum network development (left) and examples of the applications possible at each stage (right).
Source: Wehner et al., Science 362, 303 (2018).

Scientists in Delft achieve a global first: on-demand quantum entanglement

A research team at QuTech in Delft has succeeded in generating entanglements between two quantum chips faster than such entanglements are lost. Entanglement – once described by Einstein as 'spooky action at a distance' – is the phenomenon that will underpin a (future) quantum internet's power and fundamental security. Using a new smart entanglement protocol and careful entanglement protection, the team achieved on-demand quantum link generation for the first time anywhere. That opens the way for the interconnection of multiple quantum nodes and thus the world's first true quantum network. Their results appeared in the June 2018 edition of Nature.

It wasn't the first time that the team made headlines around the world.[12,13] Three years earlier they achieved another global first, generating quantum entanglement between electrons over a large distance (1.3 kilometres) and thus providing experimental evidence for quantum entanglement. Their experiment involved entangling individual electrons in mutually remote diamond chips using light particles as intermediaries. Its methodology underpins their current approach to quantum internet development.

2.2.4 Quantum sensors

Quantum sensors are instruments capable of observing variations in the environment, such as changes in temperature, radiation, acceleration, time (clocks) and electrical or magnetic fields. Unlike classical sensors, quantum sensors rely on quantum phenomena, such as entanglement, to detect variations. Quantum sensors are extremely sensitive and therefore enable more precise measurement. They are also capable of extremely high resolution, meaning that minuscule structures such as DNA can be measured.

Laboratory prototype measurement systems based on quantum sensors have already been shown to out-perform classical systems in various respects. The first generation of systems that utilize quantum sensors is now commercially available; they include accelerometers and atomic clocks made by the French company Muquans[14] and by the American company AOSense[15]. However, most experimental measurement systems are not yet ready for commercial use. In order to take full advantage of the possibilities that are opening up, it is important not only that robust and reliable quantum sensors and quantum chips are developed, but also that dedicated hardware and software are developed for controlling and reading such chips and sensors.

The continuous development of quantum technology makes it probable that, before long, more quantum sensors will come on line, capable of out-performing classical sensors. For example, we can expect to see atomic clocks capable of providing absolute reference points for determining elevation, helping to secure wireless communication and financial transactions during temporary GPS failures, and dramatically improving the synchronization of radio telescopes. Meanwhile, TNO and others are working to develop sensors for use in high-tech mechanical engineering and semiconductor manufacturing, where the biggest challenges are metrological. A little further ahead, improved navigation systems, radar systems and medical detection methods will all become possible. The continuous stream of emerging new quantum sensor types, with their many new applications, is evidence that fundamental and applied research into quantum technology does pay off.

2.3 Fundamental and technological challenges

The following paragraphs describe what is currently possible and what the main scientific and technological challenges are in each of the four application areas identified in the previous subsection.

2.3.1 Universal quantum computers

Small quantum computers have now been built by various academic and industrial teams; the systems in question typically have double-digit qubit counts, and their quality varies. We are also seeing a steady stream of announcements about work starting on bigger systems, based on various technology platforms. The two platforms currently capable of supporting the biggest systems make use of 'ion traps' or superconducting qubits. Major tech corporations, such as IBM and Google, are focusing on superconducting qubits and have come as far as making an initial test version of a quantum computer available via the cloud, complete with a programming language. Intel is pursuing two lines of development: superconducting qubits and quantum dots in silicon. The latter technology offers attractive scalability potential, because it would be relatively easy to build on existing chip manufacturing technology: the semiconductor industry is based largely on silicon platforms. Microsoft is backing a different technology: the topological quantum computer. Although in theory this technology can yield an extremely stable platform, no one has yet succeeded in creating a topological qubit. In parallel, Microsoft is both developing quantum algorithms suitable for use on various qubit platforms and working on a programming language, Q#.

The biggest challenges associated with the development of a universal quantum computer are as follows:

Development of sophisticated quantum error correction algorithms

Qubits are intrinsically sensitive to noise, because superposition means that a qubit can be every possible combination of 0 and 1. Consequently, any minor flaw in the calculations can yield a false answer. Moreover, the qubits in a system often do not remain stable long enough to perform a calculation. To address those issues, error correction algorithms have been developed, which use a larger number of supporting qubits to rectify the mistakes that occur in the qubits used to perform the calculations; the system is in effect rendered fault-tolerant. That does of course imply the need for a qubit-count overhead: estimates of the number of noisy qubits needed for the creation of a single logical qubit vary from a hundred to ten thousand. The approach should mean that, when quantum algorithms are put to practical use, the risk of a faulty qubit is reduced to one in ten thousand or less.

Development of NISQ systems with a few hundred qubits

Quantum error correction and fault-tolerant quantum computation are vital for large-scale universal quantum computers to work. However, the error correction algorithms now available cannot be used in the small quantum computers developed to date. With such machines, there are simply not enough noisy qubits for a single logical qubit to be formed using the current algorithms. Furthermore, the qubits are not stable enough for fault-tolerant algorithms to run. In the short term, therefore, quantum computers will remain 'noisy'. Hence, the current phase of development is referred to as the NISQ era: the Noisy Intermediate Scale Quantum Era (a title recently coined by John Preskill, a professor at Caltech). Most observers expect that it will not be long before we see NISQ systems with a few hundred reasonably stable qubits. Although the first wave of systems will not be fault-tolerant, they should be stable for long

[12] See: https://www.nytimes.com/2014/05/30/science/scientists-report-finding-reliable-way-to-teleport-data.html
[13] See: https://www.nytimes.com/2015/10/22/science/quantum-theory-experiment-said-to-prove-spooky-interactions.html
[14] See: https://www.muquans.com/
[15] See: https://aosense.com/

enough to perform a number of calculations. Possible applications for such early systems are likely to involve machine learning.

Reducing the error rate and increasing the qubit count

Creating a large-scale universal quantum computer with full error correction and fault-tolerant software represents a huge technological challenge. By making a large number of physical qubits work in combination, a universal quantum computer could be used to perform very large calculations, even if the qubits sometimes make mistakes. However, that implies reducing the error rate of the existing systems by a factor of ten to a hundred. It also requires the number of (physical) qubits to be increased by at least a hundred thousand in order to create enough logical qubits to retain the quantum information for a sufficient length of time. One of the biggest challenges in that context is connectivity: the interconnection of qubits. Upscaling is not possible without major progress in that field, as acknowledged by QuTech, Intel and others.

Development of scalable quantum computer architecture and electronics

Like the classical computer, the quantum computer comprises various layers, in which abstract algorithms and quantum algorithms are translated step-by-step into qubit control signals. Only provisional and partial conclusions can yet be drawn regarding the best way to design that architecture, including compilers, run-time and error correction mechanisms. The architecture still needs to be translated into a concrete, scalable implementation, complete with bespoke electronics.

Systems engineering challenges

The complexity of a universal quantum computer is comparable to that of a satellite or an EUV lithography machine. One of the biggest challenges associated with building universal quantum computers is therefore the system design and integration of all the hardware and control software. The technology is currently at the conceptual stage, but as progress is made towards increasing the qubit count, many aspects are likely to be mutually influential: where chip design is concerned, material choices and process steps will influence the coherence time and accuracy of the qubits. The thermal load of the control signals to the quantum chips is linked to the available cooling capacity. The complexity of the electronics and control software is linked to the quality of the chips, and the analysis of measuring signals for error correction requires powerful computers and sophisticated algorithms with a high data-processing capacity and very rapid feedback. The design and realization of such a complex product requires a form of systems engineering control where trade-offs and system choices are made on an integrated basis, rather than component by component. TNO and Delft University of Technology have acknowledged that as a major challenge and have linked up with the Quantum Inspire project to begin working towards a broad systemic approach.

Quantum Inspire: one system for multiple qubit types

A team at QuTech in Delft is currently working on a prototype quantum computer using a broad systemic approach. The project involves researchers and engineers from various disciplines working together on a system that will be able to both emulate simple quantum algorithms on an emulator and run them on a physical hardware chip. The system has a modular structure, so that algorithms can be run on chips that use superconducting qubits, spin qubits or NV-centre qubits. Algorithms are currently still being emulated and the system is being expanded to work with physical qubits. Quantum Inspire is using SURF's national Cartesius supercomputer, which can emulate a quantum computer with up to thirty-seven qubits.

A quantum computer with 100,000 qubits will be a highly complex machine. All the individual components of a future quantum computer will have to be integrated to form a working system. And the planning of trade-offs between the various layers of a quantum computer should start in the design phase. It is generally assumed that we are still at least ten years from being able to build a large, stable quantum computer. However, various classical systems are available around the world that are capable of simulating small quantum computers. One is QuTech's Quantum Inspire[16] platform.

Ability to efficiently import large datasets

In a quantum computer, the utilization of superposition means that a small number of qubits can represent an exponentially increasing volume of data. However, there is currently no efficient means of converting a large, classical dataset to a quantum state. In the context of mathematical problems that require large data inputs, the time needed to create a quantum state would currently exceed the calculation time. As things stand, therefore, large datasets cannot be imported efficiently to a quantum computer.

Development of further quantum algorithms

Once the state of a quantum computer has been read, all that is left of the original, complex quantum state is a single, classical result. If the full power of quantum computers is to be utilized, special algorithms are required. The development of suitable quantum algorithms is a critical process requiring highly specialized knowledge. Over the last three decades, various quantum algorithmic techniques have been developed. Using the quantum algorithmic toolbox now available, quantum computers can be deployed with a view to resolving many problems more efficiently. Quantum algorithm development has clear parallels with the development of software for classical computers, and requires great ingenuity. The NIST institute in the United States maintains an extensive online inventory of the quantum techniques developed to date.[17] However, utilizing the full potential of NISQ computers and larger-scale quantum computers depends on extending the collection of known quantum techniques and on progress with the application of those techniques to practical use cases. That in turn implies research, not only into new techniques but also into the limitations of quantum computers in certain fields of application. The problems that arise in practice must also be investigated. In the shorter term, the focus will need to be on NISQ technology. Calculations with NISQ computers in turn require a set of bespoke algorithms, and therefore targeted research and development.

[16] *See: www.quantum-inspire.com*
[17] *See: www.quantumalgorithmzoo.org*

Development of methods for verifying and testing quantum software
Classical software is debugged by reading the computer's memory while the programme is running. That is not possible with a quantum computer, because reading its state while an algorithm is running would interfere with the operation. A quantum state cannot simply be copied for checking (the 'no-cloning theorem'). Verifying the result provided by a large quantum computer is no small undertaking either: often, the result cannot be reproduced on a classical computer, since a quantum computer is capable of things that a classical computer cannot do. Consequently, new methods for debugging and testing quantum software are vital for the development of large quantum computers.

Development of intuitive user interfaces
Operation of a quantum computer requires an intuitive user interface. Creating such an interface represents a challenge, because of the counterintuitive nature of quantum physics, where quantum bits can simultaneously have a value of 0 and 1. On classical computers, mental models and metaphors such as folders, desktops and windows have proved very useful. The development of similar models and metaphors is vital in relation to the utility of quantum computers.

2.3.2 Quantum simulators
Currently, the most advanced quantum simulators are based on cold atoms and ions, which are relatively insensitive to outside interference. The technologies involved have the added benefit of having already been under development for several decades. The quantum simulators developed to date make use of ten to a hundred ions or atoms. However, the systems we currently have are not programmable and cannot therefore be used to resolve more general, larger sets of problems. Some systems work with ions and atoms in combination and consequently have the advantages of both technologies. Other systems being investigated for use in large-scale quantum computers (e.g. spins in quantum dots[18], spins in diamond, superconductor circuits[19] and electrons in artificial matrices[20]) can also serve as platforms for quantum simulations, where the issue is identifying the best qubit for each system. The particular characteristics of the various platforms make them suitable for various open questions.

Within the European Quantum Flagship, the PASQuanS project[21] is aiming to realize a fully programmable quantum simulator with a thousand atoms or ions within four years. The team's ambition is to create the first quantum simulator to demonstrate a 'quantum benefit' by resolving optimization problems that would probably exceed the capabilities of classical methods. Quantum simulators can also be used to design other systems, such as semiconductor structures. The Quantum Flagship's QOMBS project[22] is developing a quantum simulator based on cold atoms in a matrix, which will be used to design a new 'quantum cascade laser frequency comb'. The complex technology involved can have a major impact on the development of quantum communication and quantum sensors.

The biggest challenges associated with the development of quantum simulators are as follows:

Scaling up towards a thousand qubits
One of the next steps is to develop and realize a quantum simulator with a thousand qubits. Although the qubits do not need to be fully controllable for the simulations, taking that step represents a complex challenge, not least in engineering terms. It will be far from easy to contain such a large system, to prevent excessive interaction with the outside world and to enable the results to be read and interpreted. A lot of development work also needs to be done before we are able to create programmable qubits on a sufficiently large scale, so that, for example, atoms and ions can be programmed from outside using electromagnetic signals. A platform based on electrons in artificial matrices looks like the most promising option, since that would allow fully automated realization.[23] The challenges associated with promising simulator systems based on qubits on chips are similar to those described in 2.3.1.

Development of new quantum algorithms
In parallel with development of the hardware, it will be necessary to develop quantum algorithms suitable for larger-scale quantum simulators. Blueprints for such algorithms are currently being devised by, for example, researchers at QuSoft and QuTech. TNO and Leiden University are also active in this field.

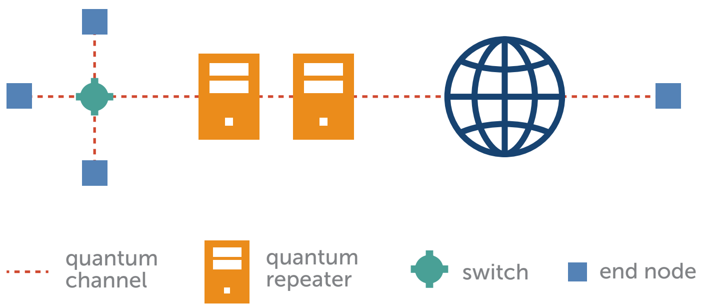
Verification and validation
Once the point is reached where the complexity of a quantum simulation exceeds the capabilities of classical simulators, determining the reliability of the simulation result becomes problematic. There is accordingly a real need for methods of verifying and validating quantum simulation outcomes.

2.3.3 Quantum communication
A global quantum internet will necessarily be preceded by various stages of development, each of which will enable new applications (see Figure 4). The simplest form of quantum communication involves utilizing the quantum properties of, for example, light particles to secure classical information, such as that transmitted via fibre-optic cables or satellites: an application known as Quantum Key Distribution (QKD). QKD is an important technology, which involves the use of a separate information channel that relies on the quantum properties of light to transmit a (classical) encryption key. If anyone tries to intercept traffic on the relevant channel, the intervention is immediately apparent to the communicating parties. QKD is useful for securing critical data that needs to remain secure for a prolonged period. The technology's first applications are therefore likely to be in the financial services sector and in the field of national defence and security. It is also anticipated that, at a later stage, post-quantum cryptography will play an important role in securing data against maliciously deployed quantum computers. For further information on this topic, see subsection 3.2.1.

Europe leads the way on the development of QKD technology, partly because of the work of the Swiss-Korean company ID Quantique, which is already marketing first-generation QKD products. With an eye to the development of a pan-European QKD network, researchers are seeking to identify other potential applications of QKD; the possibilities will become clear over the next few years. Further development work will also be directed towards eliminating potential weaknesses, such as reliance on the performance of photo detectors. The recent invention and prototyping of 'measurement-device-independent QKD' is a good example of the promising progress being made.

Communication networks capable of taking full advantage of the unique possibilities afforded by quantum physics will require more complex technology. Figure 5 sketches the elements of a quantum network. Like the classical internet, the network is made up of various components: fibre-optic connections and/or 'free-space' connections, 'quantum repeaters' that amplify the signal in transit, 'end nodes' (small quantum computers for sending signals and making calculations with the qubits), 'switches' for routing data packets within the network, and so on. The Netherlands already has the basics required for the development and scale up of quantum networks and a quantum internet. Besides hardware components, a quantum internet will require specialist software, both to control the hardware and internet traffic and to run applications on the various connected quantum computer systems.

[18] *Nature, 'Quantum simulation of a Fermi-Hubbard model using a semiconductor quantum dot array', T. Hensgens et al., Nature 548, 70–73 (2017).*
[19] *See: www.nature.com/articles/d41586-018-05979-0, www.nature.com/articles/nphys2251*
[20] *See: www.nature.com/articles/nphys4105, www.nature.com/articles/s41567-018-0328-0*
[21] *See: https://pasquans.eu*
[22] *See: www.qombs-project.eu/index.php/Home*
[23] *See: www.nature.com/articles/nnano.2016.131*



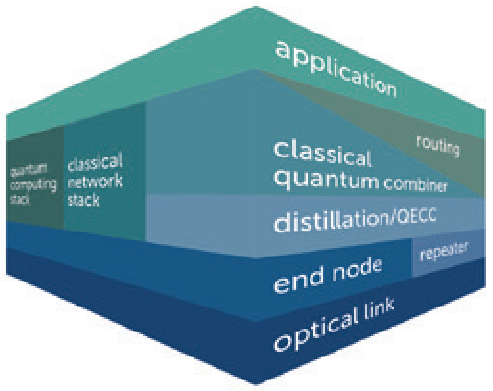


FIGURE 5
Schematic representation of the basic elements of a quantum internet (left: hardware components; right: quantum internet stack). Figures from Wehner et al., Science 362, 303 (2018).

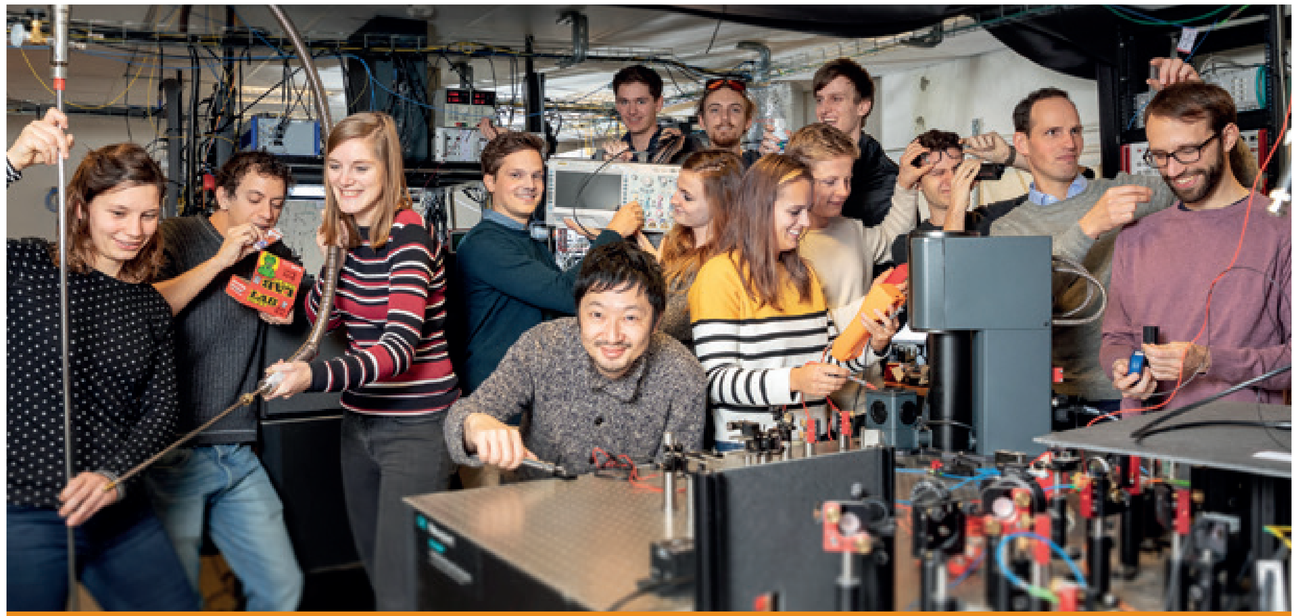
The main challenges associated with realization of a quantum internet are as follows:

Realization of entanglements over large distances
The greatest distance over which prolonged entanglement has so far been achieved between two quantum nodes (a 1 qubit quantum computer) connected by fibre-optic cableis 1.3 kilometres. The next challenge is to scale up the quantum link between two qubits connected via a standard fibre-optic cable to somewhere between 30 and 100 kilometres. That will require adaptations to the frequency (colour) and stabilization of the photons. Entanglement over even larger distances will require quantum repeaters. Such devices will have to be fundamentally different from classical repeaters or amplifiers, since any in-transit processing will break the entanglement between the qubits. The repeaters will therefore need to rely on a process of 'alternating entanglement' at each relay station: if end point A is entangled with repeater R, which in turn is entangled with end point B, repeater R can bring about an effective entanglement between A and B. To make that possible, repeater R will briefly require a quantum memory.

Realization of complex end points: quantum processors in the quantum network
For a quantum internet's first useful applications (e.g. secure identification and communication), a quantum link can function with end points (quantum processors) that each have just a single qubit. However, more complex processing and extra functionality (e.g. 'blind quantum computing' and distributed quantum computing) require quantum processors with multiple qubits and a quantum memory. Greater complexity still will - in the form of processors with multiple entangled qubits - be needed for error correction at the end points of the quantum links.

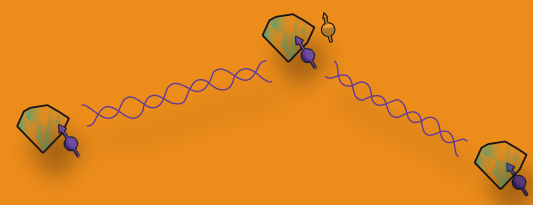
Architecture of the quantum network
As well as hardware components, a quantum internet will require specialist software to control the hardware and internet traffic. A Delft-based team has written an IETF draft[24] of the world's first link layer protocol[25], the adoption of which will make the realization of entanglement in a fundamental physics experiment a clearly defined network service. Other significant topics include developing a comprehensive quantum internet stack design featuring both hardware and software, and ensuring interoperability between network layers. A quantum-secured authentication method will be required as well, so that external users can access

[24] *The IETF is the Internet Engineering Task Force, the internet's standardization body.*
[25] *'The Link Layer service in a Quantum Internet', A.D. Dahlberg et. al., IETF draft, March 11, 2019.*



World's first entanglement-based quantum network

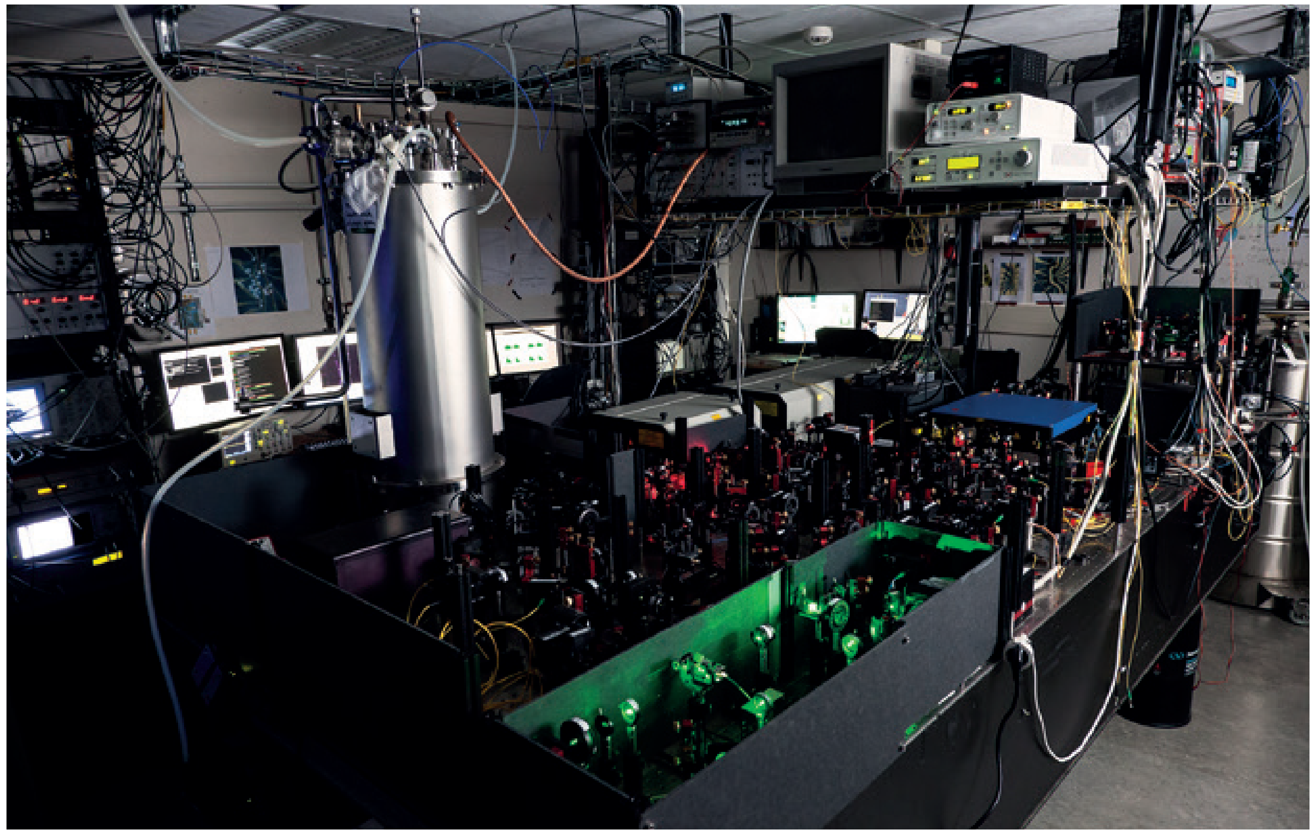
In the QuTech laboratories on the campus of Delft University of Technology, a research team is building the world's first entanglement-based quantum network. The network will use defects in diamond ('nitrogen-vacancy centres') as quantum bits, which can be entangled using light (see diagram on the right, below). The aim is to realize entanglements across a network of three 'quantum nodes'. The configuration will also allow for testing of the 'quantum repeater' concept, where entanglement is in effect relayed in order to facilitate networking over great distances. The project represents a vital step towards the realization of a large quantum internet.



the quantum network securely on the basis of quantum principles, rather than on the basis of forgeable, or crackable, classical methods, such as passwords, numeric codes, or classical, physical objects.

Software for quantum internet applications
Each stage in the development of the quantum internet will require the invention and development of new applications. Initially, the focus will be on applications in the security, governmental and financial sectors. As the complexity of the quantum internet increases, applications involving multiple interconnected quantum processors, such as clock synchronization and distributed quantum computing, will become possible.

2.3.4 Quantum sensors
Sophisticated quantum sensors make use of quantum coherence (superposition), quantum correlations and entanglement between particles in different systems to achieve higher sensitivity and resolution than are possible with classical sensor systems. Detectors (and sources) based on particular quantum principles have been under development for several decades. The Netherlands is recognized as one of the world's leading nations in this field, thanks to initiatives such as the development of sources of ultracold atoms (e.g. for atomic clocks). The technology surrounding ultracold atom sources, photon sources and photon detectors is already quite mature, for example in relation to measurement of the quantified phase and polarization. The measurement of correlated quantum properties is also within reach.



One of the endpoints or quantum nodes of the quantum link between Delft and The Hague, which is to be extended to cover the western conurbation and in due course possibly the whole of the Netherlands, en route to an entanglement-based quantum internet infrastructure. (Source: QuTech)

Work is also being done on quantum imaging techniques and sensors that utilize ultracold atoms, including extremely precise gravity sensors and atomic clocks. One important initiative in this field is a European Quantum Flagship project called iqClock[26], which is coordinated from Amsterdam. iqClock has two goals: to develop a new type of ultra-accurate optical clock and to develop an integrated, mass-producible clock, which British Telecom intends to use for network synchronization.

The biggest challenges associated with the development of quantum sensors are as follows:

Development of new sensor technologies
Much remains to be learnt about the best methods for quantum sensors. The use of intelligent optimum quantum control protocols in fields such as selectivity and sensitivity is expected to prove a fertile line of development. For example, quantum sensors are not yet making full use of all the possibilities afforded by the second quantum revolution, such as entangled states. Production and utilization of the more subtle correlations between the various sensor components (e.g. ultracold atoms, ions, NV centres, etc.) open the way for more robust and precise sensors, such as the superradiating clocks being developed in the iqClock programme.

Reducing the footprint of quantum sensor systems
Although quantum sensors are themselves (very) small, the experimental measurement systems associated with them are often considerably bigger. The footprint (dimensions, weight, cost, electrical power requirement) of quantum sensor systems can be reduced by integrating and adapting such measurement systems. That will increase the utility and scalability of quantum sensors and is vital in terms of the market-readiness of such sensors.

[26] *See: www.iqclock.eu/*

Development of scalable production processes
Many quantum sensors use unique materials, such as diamond and superconducting materials. The widespread adoption of quantum sensors will depend on the development of (semi-)automated processes for the uniform, high-quality production of such materials.

Acceleration of quantum sensors
The utility of current quantum sensors is compromised by the data readout speed. Many of the present generation of sensors use just a handful of light particles or electrons, and there is significant scope for optimizing them in order to accelerate the measurement process and increase their range of possible applications. By enabling photon detectors to handle a bigger photon stream, for example, many new applications can be brought within reach, including long-range QKD systems.

Development of fast, high-efficiency detectors
Various companies around the world already sell detectors for the detection of individual photons. However, significantly higher detection speeds and efficiencies are needed - to realize maximum key distribution speeds in the context of Quantum Key Distribution, for example. Such developments go hand in hand with the development of fast and reliable photon sources capable of emitting individual or entangled photons.

2.3.5 Challenges in other fields
The technological developments described above relate mainly to the qubit itself and to the system associated directly with it. They appeal to the imagination and therefore have a high profile. However, the maturation of quantum technology depends on overcoming challenges in other fields as well. Between the qubits and the outside world, for example, there are numerous layers of technology requiring development. New solutions are also needed in fields such as nanotechnology, photonics and materials science in order to control and measure quantum states at extremely low temperatures, to control light on extremely small scales and to protect extremely precise sensors against noise. Another challenge is that the most appropriate materials for many of the quantum technologies currently under development have yet to be determined. Various non-technological challenges need to be addressed as well: talent development and social embedding of the technology are, for instance, essential to the success of the global quantum revolution.

2.4 Conclusion

Quantum technology enables things that are not possible with classical technology. The key application areas are quantum communication, quantum computers, quantum simulators and quantum sensors. A number of small-scale, first-generation applications are already available, but most quantum technologies require significant further development before they are capable of yielding a benefit over classical techniques. Countless technological and scientific challenges remain to be overcome. While many more years of research and development are therefore needed to fully realize the potential of quantum technology, new products and spinoffs will be realized at every step on the road leading towards that goal. Indeed, the landscape is already dotted with examples. Major corporations are investing in research programmes here in the Netherlands; the first startups and spinoffs of such collaborative initiatives are appearing, and more and more interested parties (high-tech component suppliers, etc.) are setting up around knowledge institutions, laying the foundations for a Dutch quantum ecosystem.

> ‘Quantum technology can help to resolve all sorts of social challenges and create opportunities for all sectors of the economy.’

03

THE SOCIAL AND ECONOMIC IMPACT OF QUANTUM TECHNOLOGY

3.1 Short and long-term impacts

Quantum technology harnesses principles of quantum physics for practical applications. As discussed in Section 2, the most significant phenomena in quantum physics are superposition and entanglement. Those phenomena provide a basis for such fundamentally new possibilities that quantum technology is justifiably regarded as a key technology, with the potential to become a game-changer in many social and economic sectors.

The development of quantum computers, quantum communication systems, quantum sensors and quantum simulators can help to resolve social challenges and create opportunities for all sectors of the economy. Although quantum technology already has various practical applications, a great deal of further development is required before we can realize a fully-fledged quantum internet or a large universal quantum computer. While the development horizons are correspondingly distant, investments made in quantum technology now may be expected to begin bearing fruit within a few years, as illustrated in Figure 6.

The four horizontal bars in the illustration represent the developments in quantum technology's four application areas (communication, computing, simulation, sensing) over the next fifteen years, including various 'staging posts' in each area. The staging posts symbolize possible applications, products and services that are likely to become available in the years ahead. Some of the main developments anticipated are considered below.

In the next five years: Fundamentally secure communication based on Quantum Key Distribution. First-generation QKD systems are already commercially available from, for example, the Swiss company ID Quantique. Indeed, during its last elections, Switzerland used QKD technology to secure the internet connections between vote telling stations and the result collation venues. More recently, investment houses on New York's Wall Street acquired a QKD link to their back offices in New Jersey.

In the next five years: Just as a classical computer is unusable without appropriate software, a quantum computer is of no value unless good quantum software is also available. To a significant extent, the necessary software, algorithms and techniques are already being developed, often in collaboration with the industries where they will be used.

In the next five years: Quantum simulators that can serve as small, noisy, analogue quantum computers for the resolution of specific problems (NISQ, see subsection 2.3.1). Various hardware and software giants, including Google, IBM, Intel, Rigetti and China's Alibaba, are very interested in the development of these machines. Research and development work on these quantum simulators is being done at various centres in the Netherlands, including Eindhoven, Delft and Amsterdam. A number of first-generation quantum computers, typically having ten to twenty qubits, are already available in the cloud to the research community for testing simple algorithms, some on a commercial basis. Within five years, we should also see the realization of a fully programmable quantum simulator with a thousand atoms or ions, capable of delivering a 'quantum benefit' for the first time.

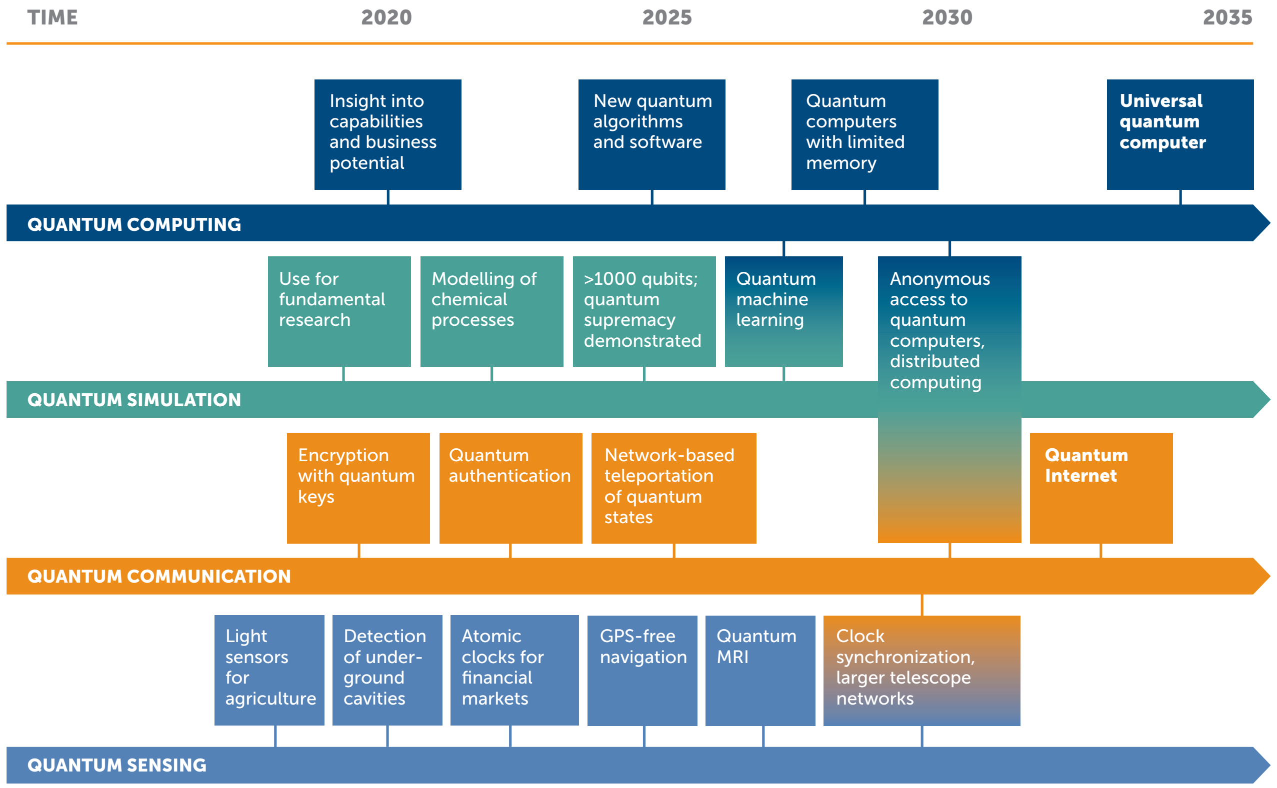


FIGURE 6
Forecast developments in quantum technology and the associated applications in the coming decades.

In five to ten years from now: Developed as part of the European Quantum Flagship project, the Quantum Technologies Roadmap[27] predicts that sensors with single-quantum precision will be available about five years from now. Networks of quantum sensors are likely to follow within ten years, the roadmap suggests, while integrated systems-on-a-chip, such as a chip-integrated atomic clock, will take a little longer. Potential uses of such quantum sensors exist in, for example, the health care domain (e.g. high-sensitivity MRI), the defence domain (e.g. submarine and bunker detection networks), the semiconductor domain (e.g. new metrology applications based on high-resolution, ultra-sensitive quantum sensors) and the agricultural domain. Such sensors can also be useful in astronomy (LOFAR, Einstein Telescope).

In five to ten years from now: Ultra-precise quantum atomic clocks already exist in laboratories. The systems in question are based on the radiation frequency of energy transfers among groups of atoms or ions in cooled systems. The challenge is now to make such clock systems smaller and more robust, so that they can be carried by satellites, for example. Used in combination with GPS, the clocks can form the basis of navigation systems with a very high level of timing, stability and traceability, suitable for use even in places where GPS cannot be used. Similar timing solutions are also likely to be valuable in future smart networks, e.g. for the synchronization of signals in energy and telecom networks.

[27] See: https://qt.eu/newsroom/quantum-technology-roadmap/

More than ten years from now: A global quantum internet, where ultra-secure quantum encryption is combined with classical data traffic transmitted via fibre-optic cables and satellites. Another possibility is a quantum link between mutually remote quantum computers, thus creating a single large, distributed quantum computer.

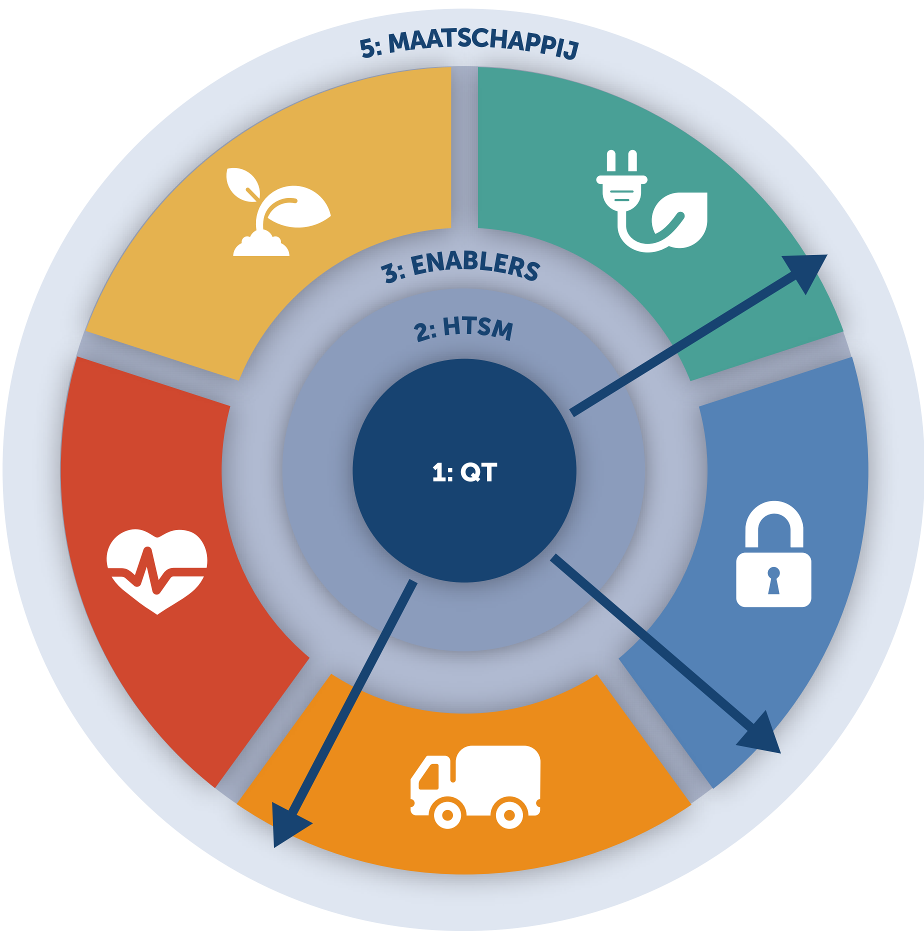
More than ten years from now: Universal quantum computers capable of solving problems that are fundamentally unsolvable for classical computers, such as the resolution of complex optimization challenges or the prediction, simulation and modelling of the behaviour of molecules, catalysts and new materials. Other possibilities include cracking conventional encryption methods, resolving complex optimization problems, rapid database searching and sophisticated forms of machine learning (artificial intelligence).

The development of a generic, fault-tolerant quantum computer and a European or even global quantum internet are challenges whose complexity and ambition are comparable with the space programme or the development of the semi-conductor industry. Just as those developments produced countless spinoffs, investment in quantum technology can be expected to yield all sorts of as yet unimagined applications. Those applications can in turn support new industries and possibly even new economic clusters. History shows that it is extremely difficult to accurately predict what applications will flow from disruptive technological developments. We will inevitably see the emergence of products and applications in addition to, and to some degree different from, those currently envisaged, even within the next few years. Investment in quantum technology can therefore be expected to yield rewards not only in the distant future, but also in the relatively short term.

3.2
Impact on all social missions

Quantum technology will permeate society via the 'arrows' in Figure 7. At the centre of the figure we see the technology itself and the research undertaken largely in universities and institutes (circle 1), often in collaboration with the business community. The next circle (2) represents the development and implementation of quantum technology-based applications, products and services building on that research, by and with industrial partners, mainly in the high-tech systems and materials and ICT sectors. A thriving ecosystem, a sound infrastructure, talent development, and the development and use of related technologies (e.g. photonics, artificial intelligence, blockchain, nano-manufacturing and materials science) will be vital; those enabling activities are depicted by the third circle. Ultimately, applications will emerge in the other (top) sectors, represented by the five segments of the fourth circle, each of which is linked to a mission and associated social challenges. The outermost circle represents the ultimate impact of quantum technology in society. Quantum technology's social impact will be discernible most readily in relation to the missions, as described in this subsection.

In the 1990s, it was thought that the greatest potential of quantum computers and quantum networks lay in the domain of security and defence. That belief was based on the development of Shor's quantum computer algorithm, which was seen as opening the way for circumventing conventional data encryption. When it became clear that a generic quantum computer capable of running Shor's algorithm was more than ten years from becoming reality, as illustrated in the previous subsection in Figure 6, and meanwhile the first 'noisy' quantum computers (NISQ), quantum sensors and quantum network applications began emerging, actors in other domains started to recognize the potential of quantum technology. Potential users of quantum technology can now also be found in sectors such as financial services, energy, agriculture, chemicals and pharmaceuticals, high technology (artificial intelligence, machine learning, cyber security) and logistics (and planning). Potential applications and the associated users in each of the five social missions are considered in the following subsections.



1 Fundamental research
- Quantum Communication
- Quantum Computing
- Quantum Simulation
- Quantum Sensing
- Quantum Algorithms
- Post-quantum Cryptography

2 Development and introduction of applications, products and services
- Hardware
- Software
- Supply Chain

3 Enabling factors
- Ecosystems, infrastructure
- Talent development
- Related technologies

4 Application to the missions

Health and health care

Agriculture, water and food supply

Energy and sustainability

Security

Mobility and logistics

5 Social impact

FIGURE 7
The permeation of quantum technology into society.

3.2.1 Security and privacy: post-quantum cryptography and quantum networks, computers and sensors

A generic, error-correcting and fault-tolerant quantum computer could potentially negate the encryption techniques currently used to secure data. Many existing encryption methods would then become fundamentally insecure. An important and widely used group of encryption methods are based on mathematical problems. One example is RSA encryption, currently used for most online data protection. Central to RSA encryption is the fact that, although the multiplication of two very large prime numbers is very easy, the reverse calculation - factorizing a very large number into two prime numbers - is extremely difficult. No fast and efficient algorithms are available to perform the task, and it cannot therefore be accomplished within a realistic time frame using a classical computer (providing that the numbers are large enough). In 1994, however, US mathematician Peter Shor demonstrated that, in principle, a quantum computer will be capable of quickly calculating the prime factors of a very large number, thus rendering many existing encryption techniques insecure.

That is seen as a serious threat, even though a quantum computer capable of performing such calculations doesn't yet exist. After all, vital (national) security information often has to be retained for decades; the possibility of a malicious party acquiring encrypted sensitive information and then simply waiting until a quantum computer becomes available therefore has serious security implications. Both national security data and private financial or medical data are potentially vulnerable to such a scenario. Developments in the field of post-quantum cryptography are intended to counter the associated threats.

Alongside post-quantum encryption, quantum encryption is also an important discipline. The difference between quantum and post-quantum encryption is that quantum encryption uses quantum hardware to secure information, whereas post-quantum encryption does not. That distinction is quite fundamental: the way that computers in quantum networks connect securely is completely different from anything that conventional computers can do. In a quantum network, the phenomenon of quantum entanglement is used, meaning that any attempt to intercept data or otherwise harvest data is immediately apparent. The most mature quantum communication technology is currently Quantum Key Distribution (QKD). For example, we already have 'prepare and measure' QKD protocols, based on superposition. The quantum information transmitted is used to derive a shared key, which is then used to secure communications sent via the classical internet. A secure authentication method will have to be developed as well, to ensure that access to quantum computers and the quantum network is indeed restricted to authorized users. Such a method might be based on software, or on physical objects.

Quantum sensors also have potential applications within the security domain. They can, for example, be used for military or security purposes, such as navigation in circumstances where GPS cannot be used (e.g. in enemy territory, or underground). Quantum gravitation sensors can also be used to detect submarines. Moreover, optical atomic clocks on submarines, ships or aircraft can used to detect the manipulation of GPS signals. Another possibility is to install atomic clocks in telecommunications networks, enabling them to continue operating in the event of the GPS system going down. According to one recent report, the outage of GPS and telecommunications networks would cost hundreds of millions of dollars a day in the US alone.[28]

Preparing for quantum computers by developing post-quantum cryptography

The most popular cryptographic 'public key' protocols currently in use would be vulnerable to an attack launched using a quantum computer. The protocols rely on mathematical problems that are very difficult to solve using classical computers, such as calculating the prime factors of a (very) large number. However, such problems could be solved quickly by an as yet hypothetical large, stable quantum computer. That has led to the emergence of post-quantum cryptography: a branch of cryptography concerned with the development of modern, algorithmic encryption methods that would not be vulnerable to quantum computer attacks. Much more research - involving collaboration between quantum algorithm experts and cryptologists - will be required to develop new protocols that cannot be circumvented using quantum algorithms. Among those active in the field of post-quantum cryptography are KPN, QT/e and QuSoft; Microsoft and Google are also taking a keen interest. TNO is working on products and strategies for helping organizations to become quantum-resistant as well. Meanwhile, on the international stage, progress is being made towards the standardization of post-quantum cryptography protocols.

[28] *'Economic Benefits of the Global Positioning System (GPS)', RTI, Report Number 0215471, Sponsored by the National Institute of Standards and Technologies (NIST), USA.*

Quantum Key Distribution (QKD) makes ultra-secure communication possible

The first generation of QKD products is already commercially available. One drawback of these early QKD systems (which use fibre-optic links) is that the maximum physical separation between machines is currently about 50 to 100 kilometres (although tests have been carried out involving separation distances exceeding 400 kilometres). Moreover, the systems are not yet totally secure. The problem is that the conventional amplifiers used in fibre-optic networks do not work with quantum communications. Various teams, including researchers affiliated to the Quantum Internet Alliance in the Netherlands, are therefore working on the development of special quantum repeaters.

Meanwhile, the first steps have been taken towards bridging intercontinental distances by communicating via space. 'Free-space QKD' harnesses the quantum mechanical properties of light in combination with laser-satcom technology, in order to transmit encryption keys for ultra-secure communication. In 2016, China launched a satellite that was used for exploratory experiments leading towards the transmission of quantum data through space, between one or more satellites and terrestrial receiving stations. Various other countries, including Canada, Singapore and the UK, are also working on free-space QKD missions. At the European level, the ESA ScyLight programme features several space-based QKD projects, in which TNO and various Dutch companies are involved. Recently, a new Dutch project got underway: QuTech and ABN AMRO bank will be working together to develop quantum-secured connections for the financial services sector.[29]

The social impact of the developments outlined in this section will be considerable. Moreover, security and privacy have knock-on effects on other domains and applications. For example, the ability to communicate more securely via a quantum internet could promote the application of new digital technologies, such as artificial intelligence, machine learning and cloud computing. In the future, it would also be possible to securely connect multiple quantum computers via a quantum network. That will open the door to a whole range of new possibilities, including networked quantum computing and unanimous, secure calculation on quantum computers via the cloud.

3.2.2 Energy and sustainability: quantum simulators, computers and sensors

By utilizing phenomena such as superposition and entanglement, quantum computers are capable of the parallel processing of exponentially greater volumes of data than classical computers can handle. Moreover, by using quantum simulators, quantum systems can be modelled on a much more natural basis, opening the way to calculating the various states of molecules or chemical compounds, for example. A quantum simulator is a controllable and manipulable quantum system capable of predicting the behaviour of another quantum system that is being investigated.

[29] See: https://medium.com/abn-amro-developer/abn-amro-investing-in-quantum-technology-cce474fe430f

Using quantum computers to design complex molecules

With financial support from Shell Research, a research team has been established at Leiden University which, in collaboration with Vrije Universiteit Amsterdam, will investigate the possibility of using a quantum computer to design complex molecules. Artificial photosynthesis and an environmentally friendly artificial fertilizer production technique are two of the applications on the horizon, which would be impossible for even the most powerful conventional computers. The illustration (source: Wikipedia) depicts the complex enzyme nitrogenase, which is vital for environmentally friendly artificial fertilizer. Modelling the molecule is too complicated for a conventional computer, but should be possible for a quantum computer.

Quantum simulators and quantum computers can facilitate the formulation of solutions to energy and sustainability issues. For example, they can be used to identify suitable materials for manufacturing better batteries, to develop new types of solar panels, or to design new, less temperature-sensitive superconductors for use in energy transmission. They are also of great potential value in the context of optimization challenges in the fields of power grid design and energy distribution. Furthermore, sensors that use quantum technology can map the Earth's gravitational field with unprecedented accuracy, facilitating geological activities such as carbon storage, volcanology and exploration. Quantum technology's potential impact on the energy transition is therefore considerable.

Research teams at various Dutch universities (Eindhoven, Amsterdam, Leiden, Delft and Utrecht) are working on the development of quantum simulators. In a number of cases, the initiatives involve private sector partners. For example, Shell and Leiden University have started a joint project that addresses issues relating to quantum chemistry and photosynthesis.

3.2.3 Health and health care: quantum computers, simulators and sensors

The ability to simulate quantum processes means that quantum computers and simulators have great potential in the health and health care domain as well. The reason being that all nano-scale processes and systems, including those in the human body, are governed by the laws of quantum physics. Although small-scale processes can be simulated and analytical calculations made using a classical computer, modelling larger systems (larger molecules, complex processes) requires more computing power. So, for example, modern supercomputers can just about make calculations for a caffeine molecule, but not for a penicillin molecule.

Molecular interactions at the (sub)atomic level are crucial in the context of research into new medications. If in the future all the proteins that humans can produce (of which there are more than twenty thousand) could be modelled using quantum simulators, including their interaction with established or newly developed medications, that would have far-reaching implications for health care and pharmaceuticals. While that scenario is probably several decades away, quantum computers and simulators are in principle capable of making it reality.

Quantum sensing for use in hospitals: nano-MRI

By making use of defects in the crystal matrix of a solid such as diamond, it is possible to create extremely sensitive and versatile quantum sensors. Both the sensitivity and the resolution of such sensors is very high. They are also suitable for use at a range of temperatures, including room temperature. Quantum sensors can be used to measure a variety of microscopic and nano-scale phenomena, including electric currents, magnetic fields, electrical charges, temperature, pressure and mechanical forces. Numerous applications are being developed by teams in many different countries. They include nano-scale MRI applications for use in materials science and biochemistry, the characterization of quantum materials, GPS-free navigation, the quality control of hard discs and batteries, and the detection of plastic pipes.

Possible future medical applications are being investigated by various consortia as well. The MetaboliQs[30] Quantum Flagship project, for example, is harnessing defects on the surface of a diamond to polarize pyruvic acid (a breakdown product of sugars, fats and proteins). The pyruvic acid produced enables the detection of vascular conditions by means of MRI scanning, many times more quickly than is possible using conventional techniques. In 2018, a NWA project was started, in which Delft University of Technology, QuTech, Leiden University, TNO and two startups (Applied Nanolayers and Leiden Spin Imaging) are developing a 'quantum microscope' that utilizes a diamond magnetic field sensor to visualize the nano-scale behaviour of electrons close to absolute zero, and at room temperature. In due course, the method can enable nano-scale MRI scanning in hospital settings.[31]

Moreover, quantum sensors have great diagnostic potential, e.g. in future MRI scanners. MRI scanners can visualize the structures of molecules and proteins, thus making tumours visible, for example. At the moment, a single MRI image requires multiple scans of a relatively large surface, which are subsequently averaged to generate one image. Using quantum sensors, which will be much more sensitive and accurate than existing sensors, it should be possible to perform more localized, ultra-high-resolution measurements.

3.2.4 Agriculture, water and food supply: quantum computers, simulators and sensors

The potential of quantum computing is often illustrated by reference to artificial fertilizer. Artificial fertilizer is vital for food production and therefore the ability to feed the world's huge and growing population. One of its main components is ammonia, but the production of ammonia by means of the 'Haber-Bosch process' is extremely energy-intensive, accounting for an estimated 3 per cent of total (global) energy production. However, some bacteria express an enzyme that is capable of producing ammonia much more efficiently. If it were possible to ascertain exactly how that enzyme works, scientists would probably be able to mimic the process. That in turn would lead to a major reduction in the demand for energy. Unfortunately, even the world's most powerful supercomputers are currently able to simulate only eight of the enzyme's 450 amino acids. By contrast, a fault-tolerant quantum computer should ultimately be able to simulate the enzyme. By fully characterizing and mimicking the enzyme, artificial fertilizer production could then be made many times cheaper and more sustainable.

Another possible agricultural application of quantum technology is the measurement of radiation in the wavelength range associated with photosynthesis. That would involve 'photosynthetic active radiation' quantum sensors. Using such sensors (already marketed by various manufacturers), it is possible to build up a detailed picture of crop growth. Quantum sensors could also be used to detect waterborne pollutants.

In the field of water management and flow calculation too, quantum computers and simulators can be of great value. Quantum simulations can resolve Navier-Stokes equations for flows in liquids and gases, enabling the simulation of turbulence around an aircraft wing, for example. Airbus accordingly set up a challenge programme, which got underway recently and is due to run throughout 2019. The company wrote: "It is open to the whole scientific community of experts, researchers, start-ups, academics and will lay the ground for the ultimate shift to a quantum era in aerospace."[32] Other possible applications include modelling the effect of high blood pressure on the heart and blood vessels, simulating processes for the chemicals industry, and predicting flooding events in low-lying regions.

3.2.5 Mobility and Logistics: quantum computers and simulators

Governments, enterprises and other organizations use classical computers to perform all sorts of search operations and to optimize countless processes: scanning large data files, finding the most efficient route through a busy city, retrieving goods efficiently from a large storage facility, formulating work rosters, designing efficient chips for aircraft, and so on. In many cases, quantum computers and simulators may well be able to perform the necessary calculations much more quickly. For example, when quantum technology is used with Grover's algorithm (published in 1996), an unstructured database can be searched very rapidly. Other potential applications of the technology

The QuantumLab: quantum computing and water management in the Netherlands

Innovation Quarter, QuTech, TNO, IBM and Microsoft are currently working to establish a field lab to develop use cases for quantum computers in the water sector. To that end, two workshops have been organized with quantum experts and potential end users from the water sector, including Deltares, KWR, Imhoff, Stowa, Danser and aFrogleap. The intention is to investigate possible ways of utilizing the power of quantum computing within the sector. There is also widespread interest in exploring quantum computers' potential for speeding up the resolution of Navier-Stokes equations, which are used for modelling in fields such as fluid mechanics.[33] The possibility of using the same field lab construction to address other use cases is being investigated, for various applications and in various sectors, including the financial services sector, cyber-security and logistical chains. Notably, resolution of the Navier-Stokes equation is one of the seven 'millennium problems': anyone who can solve a millennium problem stands to win a million dollars.

[30] *See: www.metaboliqs.eu/en/the-project.html*
[31] *See: www.nwo.nl/onderzoek-en-resultaten/programmas/nwo/nationale-wetenschapsagenda---onderzoek-op-routes-door-consortia-orc/toe-kenningen-2018.html*

[32] *See: https://www.airbus.com/innovation/tech-challenges-and-competitions/airbus-quantum-computing-challenge.html*
[33] *'Towards Solving the Navier-Stokes Equation on Quantum Computers', https://arxiv.org/abs/1904.09033*

Quantum computing for process optimization

Bosch and QuSoft are together looking into how quantum computing could be of value to the multinational. Lines of research include quantum computing's potential applications in design processes and artificial intelligence, as well as the technology's capacity to speed up optimization processes. One of the postdoctoral researchers on the project said: "As the first quantum computer gets closer to realization, it's important for enterprises to consider how quantum algorithms can help them - in optimization and simulation for product development, for example. There's a lot to be gained from ascertaining what mathematical and optimization problems are most significant for Bosch, and then to address those problems using quantum algorithms."

include determining the global minimum or maximum of a given calculation function or landscape, and establishing the shortest route between two points on a map. Use of a quantum computer for any such task does, however, depend on being able to efficiently import classical data.

Various teams and organizations have already tested quantum optimization in practice. For example, as mentioned above, Airbus has experimented with the use of quantum technology to predict airflows over aeroplane wings by means of comprehensive air particle modelling, with a view to producing more robust and efficient aircraft designs. Meanwhile, NASA has partnered with Canadian company D-Wave (which makes a particular type of quantum computer) with the aim of optimizing baggage and storage onboard spacecraft.

3.3 The economic impact of quantum technology

The quantum technology landscape has changed dramatically in recent years. A decade ago, the scientific research centres and QuTech already foresaw quantum technology having a major technological and social impact. However, that vision was not generally shared by the wider world; people were sceptical mainly about its technical feasibility. A very different situation now prevails. According to Gartner, quantum technology is currently on the upward side of the Gartner hype cycle[34]: Expectations are high, governments and enterprises are investing heavily, numerous startups are appearing, and there is considerable media interest. It seems that everyone is getting in on the act. Nevertheless, the expectations have yet to be fulfilled. Gartner's hype cycle theory predicts first a cooling-off phase, when it becomes clear that the technology is not yet mature and that various shortcomings and challenges need to be addressed. That is precisely when perseverance is needed: those that press on with focused development and experimentation with a view to advancing the technology and its applications will be best placed to take advantage in the following phase, when the market really starts to develop and commercial applications emerge and grow.

In time, quantum technology can be expected to create new market opportunities for the business community. Those opportunities are likely to be in all sectors and to fuel significant economic growth. For the time being, the extent of that effect is difficult to estimate, since a lot more development work is required before the technology can be applied and utilized on a large scale. Conclusions can nevertheless be drawn regarding the market potentially open to the providers of quantum technology-based products and services, and to their suppliers. The size and nature of that market is considered in this subsection.

[34] *See: https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018/. According to Gartner, quantum computing is on the upward side of the Gartner hype cycle. Gartner does not include quantum communication, quantum simulation and quantum sensing in the hype cycle, but those technologies are probably in a similar position.*

3.3.1 An ecosystem for quantum-based products and services

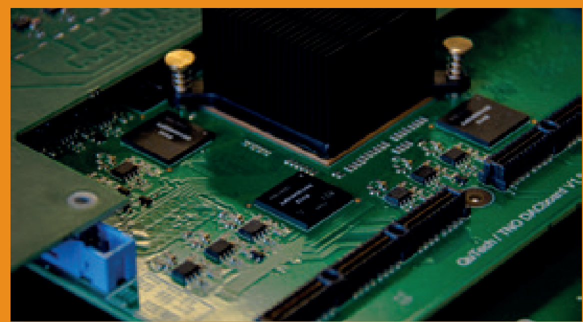
Quantum technology will initially yield opportunities for the high-tech systems and materials and ICT sectors. Together with their suppliers, various companies in those sectors are already developing quantum technology-based products and services with a view to bringing them to market. The high-tech sector is a key sector of the Dutch economy, with global players such as ASML, ASM International, NXP, Philips and Thales, as well as numerous suppliers (typically SMEs) in the Eindhoven Brainport region and elsewhere. ICT is an important sector as well, with enterprises such as KPN, Microsoft, IBM, Intel, Fox-IT, SAP and ATOS. Moreover, software companies may be expected to take on an increasingly significant role, developing applications both for quantum computers and for the quantum internet. Many of those enterprises are involved in the development of quantum technology and have contributed to the formulation of this agenda. Meanwhile, a cohort of Dutch startups are working with quantum technology, including QuiX of Enschede and Delft Circuits, Single Quantum and Qblox of Delft.

Investment in technology leads to high-quality new jobs. Consider the following illustrative estimates. In 2018, Birch Consultants investigated the scope for realizing a Q-Campus in Delft.[35] Following up the study findings, it was calculated that realization of the Q-Campus by 2023 could lead directly to the creation of 675 FTE jobs, all of them high-grade R&D posts. When the indirect impact on employment is added to the picture, the total employment effect works out at more than 2000 FTEs (including an estimated 25 per cent at vocational upper secondary level) by 2023. Calculations suggest that the total employment level effect by 2030 could be 7000 FTEs. The original study related exclusively to the Delft region; it is clear that, when the programmes in other cities and regions are taken into account, quantum technology's total employment level effect in the Netherlands will be considerably greater, both in the short term and in the longer term.

A highly simplified sketch of the quantum technology ecosystem is presented in Figure 8. At the centre is the technology itself, and the parties doing research and development work on the technology. Surrounding that core are the suppliers: companies that supply the critical

Qblox, one of the quantum startups in the Delft region

Qblox was founded in 2018: a spinoff of QuTech's activities in the field of electronics development. The company focuses on refinement of the 'stack' of electronic components needed to manipulate qubits and build a universal quantum computer.



Scaling up the existing prototype quantum computers, which have just a handful of qubits, to create computers with hundreds or thousands of qubits, depends on corresponding progress being made with the control electronics. Qblox is entering a market dominated by established electronics giants, whose standard products do not meet the quantum computing community's existing needs, and more importantly that community's future needs. The company is a textbook example of how an expertise mix (covering fields such as quantum theory, electronics and computer science) can be created to yield bespoke output and sound product support.

QBLOX

[35] *Birch, 'Building a Q-Campus: realizing a quantum ecosystem in Delft', 2018. NB: Q-Campus is merely a working title.*

components and semi-finished products for quantum computers and sensors, such as (optical) chips, lasers, cryogenic cooling systems and electronic equipment. The supply industry affords opportunities for Dutch semiconductor and photonics manufacturers and others, as well as attracting non-Dutch suppliers to invest in the Dutch market. An example of the latter group is the Finnish company BlueFors Cryogenics, which makes sophisticated cooling equipment of the kind needed to build quantum computers. In late 2018, BlueFors announced plans to open an R&D unit on the Q-Campus in Delft.

Supply companies sell to the enterprises that manufacture and market devices based on quantum technology, such as QKD equipment and quantum computers. Those manufacturers have various business models. IBM's model, for example, is based on 'hardware as a service', where the end user accesses the computing power of IBM's quantum computers via the cloud. Others sell their devices as discrete products, one such being the Canadian company D-Wave (which additionally offers a cloud service). This region of the ecosystem is also where the software needed for the devices to work (e.g. error correction software) is developed.

FIGURE 8
Simplified diagram of the quantum technology ecosystem. The pathways are shown separately, but are not in reality mutually isolated. Moreover, organizations active on one pathway or in one region may additionally be active on other pathways and in other regions. The diagram is also incomplete: government bodies, investors, umbrella organizations, NGOs, standardization bodies and others have been omitted in the interests of simplicity.

Next, we have companies that develop quantum applications and software for (and sell to) end users; end users are then able to run the applications on devices made available by hardware-as-a-service providers, or on their own quantum computers. Those parties include organizations such as the Dutch institute QuSoft, which develops quantum applications. In the same region of the ecosystem, one also finds the suppliers of products and services that utilize quantum technology. An example being KPN, which with its partners develops secure data communication solutions, for which quantum-encrypted connections are used (QKD). Such companies supply end users in various domains, who form the outermost region of the ecosystem in the diagram. Potential end users can be found in all sectors of the economy. Many of them were involved in the development of this agenda: ABN AMRO, Shell, Aramco and the Ministry of Defence were represented in the consultation group, for example, while organizations from the health care sector, the water sector and the security domain attended the open day organized to gather input for the agenda.

The Netherlands has considerable experience in the development of similar ecosystems. One obvious example is the high-tech ecosystem surrounding Eindhoven's Brainport region. The Netherlands has also been successful in ICT: a strong digital infrastructure and associated ecosystem has been developed. Parties such as Microsoft and Google have built major data centres in the Netherlands, while Amsterdam's Internet Exchange (AMS-IX) has established itself as one of the world's biggest internet hubs, with a status analogous to that of the logistics hubs at Schiphol airport and Rotterdam seaport. The ambition of this agenda is for the Netherlands to become an international centre and hub for quantum technology. After all, quantum technology dovetails well with the Dutch semiconductor cluster and developments in, for example, photonics and smart industry. Quantum technology also complements the Netherlands' position in the field of ICT and the developments in progress in artificial intelligence and machine learning.

3.3.2 The market for quantum technology

In the previously cited 2018 study, Birch Consultants estimated that the total market for quantum technology in the 36 OECD countries could grow to roughly 65 billion US dollars over the next twenty years. That figure was based on market forecasts by Morgan Stanley and OECD data. Birch's projections are illustrated in Figure 9.

Within the market for quantum technology-based products and services, three sub-markets may be defined: quantum computers (including quantum simulators), quantum sensors, and quantum communications solutions. Although a small number of early products and services that utilize quantum technology are already available - including D-Wave's quantum annealer, IBM's small universal quantum computer, the Swiss company ID Quantique's first-generation QKD solutions, and French company Muquans' atomic clocks and accelerometers - it remains unclear how big the various market segments are likely to be, or how they are likely to develop. An attempt is nevertheless made below to estimate the potential volume of each segment on the basis of (fragmented) information from various sources.

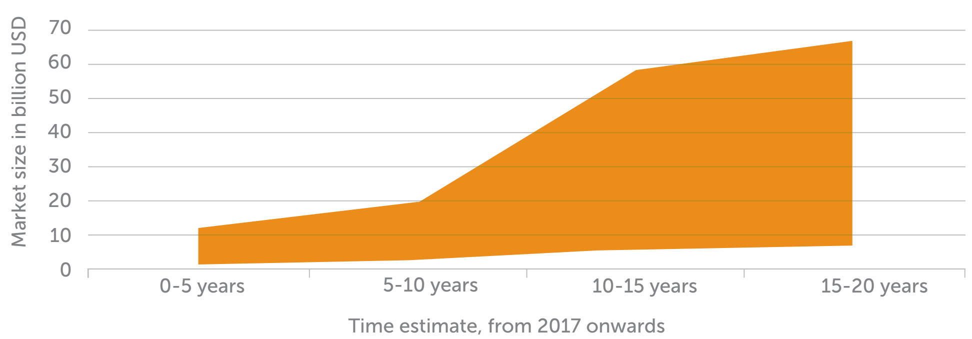


FIGURE 9
Estimate of overall growth in the market for quantum technology in the 36 OECD countries. (Source: Birch)

The market for quantum computers and quantum simulators
In 2018, BCG[36] estimated that the global market for quantum computing, quantum simulation and related services was likely to grow from 1 to 2 billion US dollars in 2030 to between 263 and 295 billion by 2050. Those figures are based on two scenarios: a low-growth scenario characterized by conservative estimates (Moore's Law applied to qubits, assuming no acceleration in the development of quantum error-correction algorithms), and a high-growth scenario (assuming that the need for error correction significantly declines, with the result that large quantum computers come on line sooner than currently expected). In either scenario, the market volume will be very significant, especially in the long term. By way of comparison, BCG estimates that the global market for computing is currently about 800 billion dollars.

However, BCG's two scenarios do differ significantly in terms of the speed of market development. That is because the speed of market development depends to a large extent on how quickly large-scale quantum computers come on line. BCG believes that the potentially addressable market in 2030 could be many times larger (about 50 billion dollars). However, realization of that potential would depend on more rapid development of the quantum computer than currently envisaged in either BCG scenario. BCG also calculates that, if it were currently possible to perform quantum simulations of complex atomic processes, the US market alone would be worth between 15 and 30 billion dollars. That may also explain why certain other consultancies (including Birch) predict the development of a larger market for quantum computers at an earlier stage: between about 2 and 10 billion dollars by 2025.[37] The agencies in question assume faster development of quantum computer technology than assumed by BCG in 2018.

The market for quantum communication and quantum sensors
Tematys recently published market research carried out for the European Union to gauge the global market for quantum communication (particularly QKD applications) and quantum sensors, such as atomic clocks.[39] The findings suggest that, in the period 2020 to 2028, the market for quantum sensors will grow from roughly 30 million euros to 210 million, while the market for atomic clocks grows from 250 million euros to 350 million and the market for quantum communications (telecom) increases from roughly 10 million euros to 300 million. Those predictions assume that QKD unit prices will fall by about 80 per cent during the same period. The study findings are visualized in Figure 10.

Three phases in development of the market for quantum computers

In November 2018, Rigetti Computing's founder and CEO Chad Rigetti had this to say about the development of the first applications and use cases for quantum computing: "I look at the quantum computing market as having three phases. The first, which we recently moved out of, was the what-is-possible phase. People could see the potential, but the big question was, can we build a programmable quantum computer? We've answered that question, yes, we've shown it can be done. We're now in the second phase, the early market phase. We know the machines are real, but nobody has actually built one and used it to solve a problem that is not also solvable using classical computers. When we do that – which is my definition of quantum advantage – we'll move into the third phase, the growth phase for quantum computing. That will be defined by the development of new markets and domains that are rooted in quantum advantage."[38]

36 *BCG, 'The coming quantum leap in computing', Massimo Russo et al., May 2018.*
37 *Including Market Research Future, AMR and Tabular Analysis.*
38 *'Chad Rigetti on the Race for Quantum Advantage', interview by BCG, November 2018.*
39 *'Market Research Study in Nanoscale quantum optics', COST Action MP1403, Tematys.*

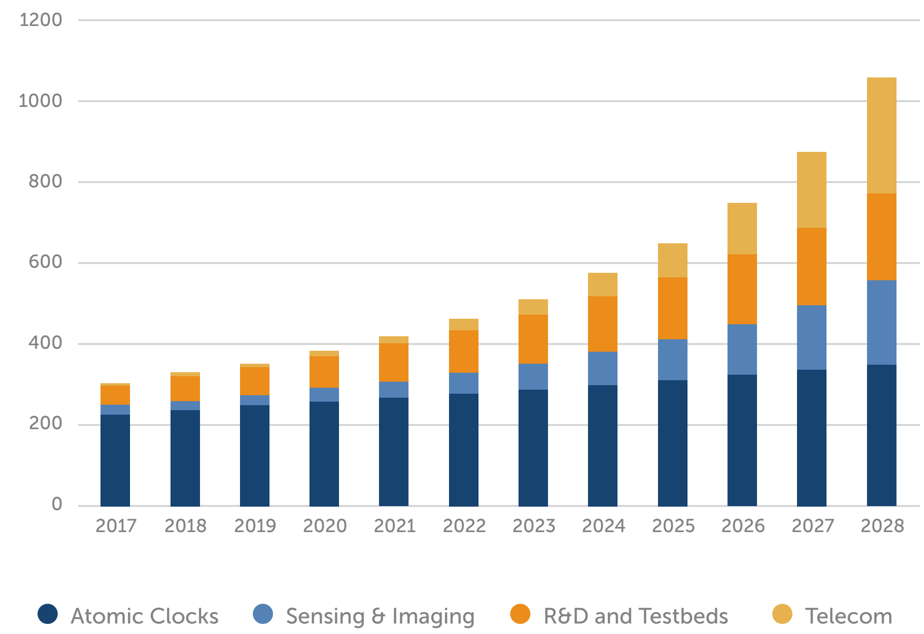


FIGURE 10
Total global market for nanoscale quantum optics, in M€. (Source: Tematys)

3.4 Ethical, legal and social impact

Most articles and analyses on this topic assume that quantum technology will have a positive influence on the economy and society. However, like any revolutionary new technology, quantum technology is not itself either good or bad. The way that the technology affects society will be determined by the people that use it. Some commentators envisage 'doom scenarios' in which quantum technology has dire consequences for security and privacy, the balance between citizens, governments and corporations, or international geopolitical relations. Questions have also been raised concerning the role of quantum computers in the development of artificial intelligence and systems that might ultimately become cleverer than people. Against that background, a number of potential risks that quantum technology poses for society are outlined below.

Risk of increased inequality
It is very likely that the first generation of quantum computers and simulators will not be equally accessible to all. That could lead to power and wealth being distributed unequally; the USA, China and Europe might benefit disproportionately relative to the rest of the world, for example, or a number of major technology companies could benefit at the expense of the rest of society. Such risks could perhaps be offset by the availability of quantum computing as a service, as exemplified by IBM's existing Quantum Experience service. Quantum computer chips can operate only at extremely low temperatures, so end users are more likely to be offered cloud services than desktop machines. If cloud services are made freely available, everyone can share the benefits afforded by quantum computing. Whether everyone can be provided with the knowledge and skill needed to make use of such services is another matter.

Risks to the stability of the financial system
Money has become a digital 'asset', with most bank transactions performed online. Quantum computing might therefore have a serious adverse effect if it enabled cybercriminals to manipulate the financial system. After all, Shor's algorithm has the potential to nullify current security provisions. Banks and other financial institutions should therefore be preparing now for the arrival of quantum computers. Fortunately, that is indeed the case, with post-quantum cryptography and QKD both being actively explored as routes to more secure communication. Standardization and certification are essential in this field, however.

Risks to privacy and security
In the future, quantum computers will be able to break most present-day public key encryption. Both national security data and personal, financial or medical data are therefore potentially vulnerable. Developments in the field of post-quantum cryptography are intended to counter the associated threats.

Quantum Software Consortium's Legal & Societal Sounding Board

In 2017, the Dutch Research Council awarded a Gravity Programme grant to the Quantum Software Consortium, a partnership involving QuSoft (as programme coordinator), QuTech and Leiden University. The 18.8 million euros of funding over a ten-year period will enable the consortium to work on software for quantum computers and quantum networks, on cryptography in a quantum world, and on quantum software demonstrators. Explicit attention will also be paid to methods for responsible innovation on the basis of the technologies in question, whose impact will transcend legal, ethical and social boundaries. To that end, a Legal & Societal Sounding Board has been established to focus on ELSA analysis, and the Board has set up a modest research and education programme.

Risks associated with state surveillance and control
Quantum technology could enable governments to keep their citizens under close surveillance. Legislation may therefore be required to prevent any negative effect on personal freedom and privacy. On the other hand, there is also a risk of the state being disempowered if criminal organizations were to gain control of quantum technology that could not be countered by the authorities.

Risks to security
The first countries to have quantum technology will, at least temporarily, have a communications and surveillance advantage over other countries. That could alter geopolitical relations. As well as enabling the simulation of new pharmaceuticals and molecules, quantum computers could also be used to create new biological and other weapons, such as weapons that target people with certain genetic characteristics. The geopolitical risks associated with quantum computing can be addressed by making the technology available to all countries. A further complication is that quantum technology enables 'blind computing': using a quantum computer to perform calculations without the host having any knowledge of what is being done. The free availability of quantum computing will therefore require regulation.

Given how rapidly the technology is developing, now is the time to instigate social debate regarding the ethical, legal and social aspects (ELSA) of quantum technology and its integration into Dutch (and European) society. The Netherlands can take the lead in that context, and play a pioneering role. A start has already been made, with a publication[40] on the quantum internet's impact on society by the Quantum Vision team at Delft University of Technology. The publication addresses matters such as enhanced privacy, governance of the quantum internet and net neutrality, and universal access. A Legal & Societal Sounding Board has also been set up by the Quantum Software Consortium (see inset text).

A precondition for social debate about quantum technology is that all participants have a reasonable understanding of the technology and its implications. After all, even 'insiders' are inclined to represent quantum technology as a mysterious manifestation of counterintuitive ideas and processes. That has implications for the participation in the debate of people from other academic disciplines, industry or government, and by the wider community. As a result, the technology's growth and social adoption could be adversely affected: society might be reluctant to accept quantum technology, or might even reject it, thus holding back, counteracting or greatly delaying integration. It is instructive to consider the acceptance issues associated with stem cell therapy, genetic modification, climate solutions and vaccination.

3.5 Conclusion

Quantum technology will have considerable impact on our society and economy. That impact will be felt both in the long term and the short term, and will affect all sectors of the Dutch economy. The possible applications of quantum computers, quantum simulators, quantum networks and quantum sensors are innumerable; we are not yet able to imagine half of everything that will be possible. At the moment, it is therefore not possible to confidently forecast the total economic impact of all the applications, products and services that quantum technology will enable. Consider the market for semiconductors: in 1943 Thomas Watson, then CEO of IBM, predicted that a global market would develop for about five computers. That was a long time ago, of course. However, many commentators remained sceptical about the market potential for many years. In 1977, for example, Ken Olsen, founder and president of DEC (a leading computer technology company of the period), wrote: "There is no reason anyone would want a computer in their home."[41] Yet today computers are an integral part of everyday life and the semiconductor industry is the driving force behind mobile applications, self-driving vehicles, and so on.

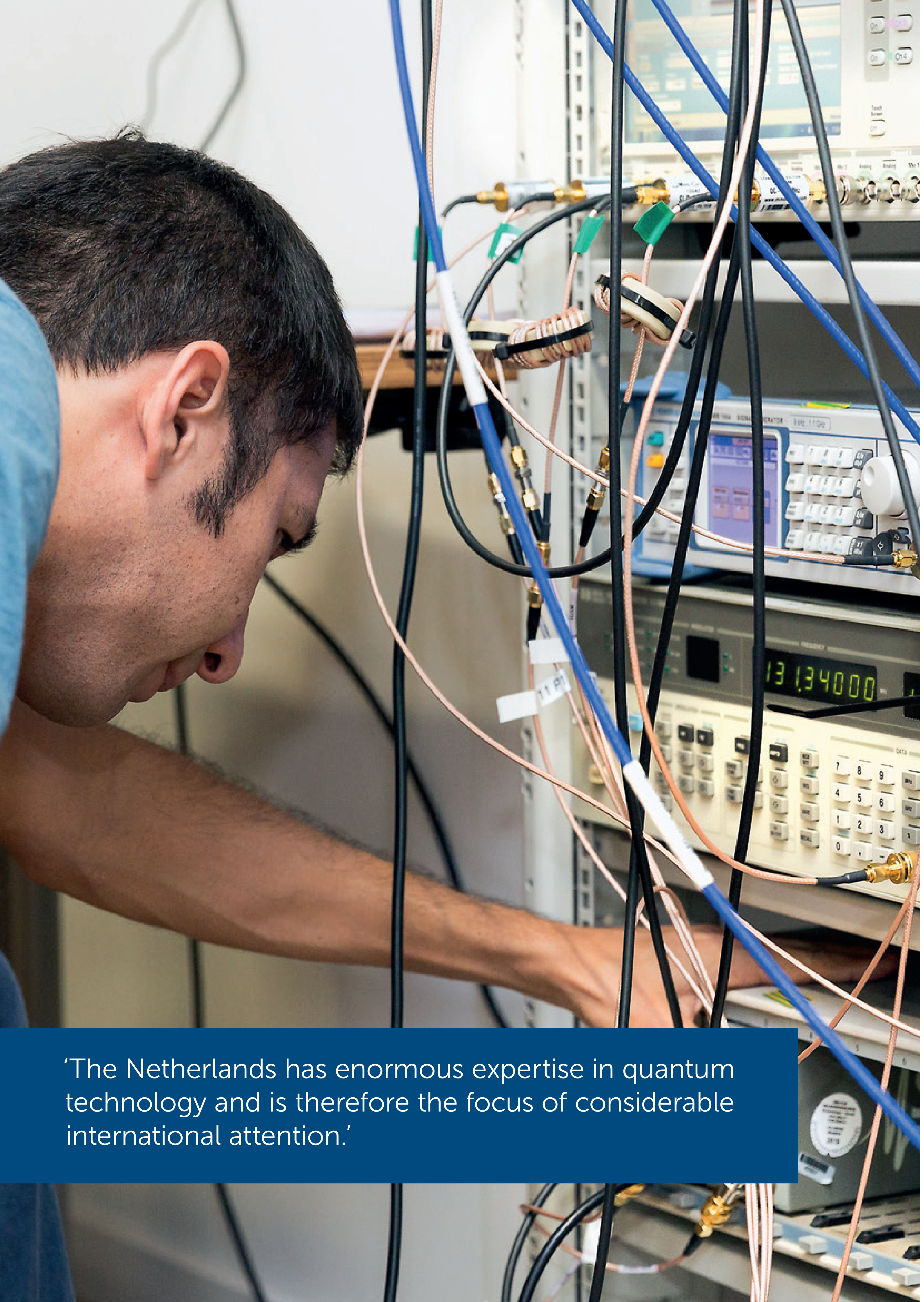
In due course, the market potential is undoubtedly very considerable. However, the timing of that potential's realization is unclear, being dependent on the rate of technological progress. We must nevertheless act now if the Netherlands is to take full advantage of the economic opportunities provided by quantum technology. Immediate investment is required in research, education, infrastructure and ecosystem development. By developing mass and excellence and getting ahead of other countries, we can put ourselves in a strong position for decades to come.

That strategy has previously been successful for the Netherlands in fields such as hydraulic engineering (building on unique knowledge and skills), ICT (where the Netherlands is a major internet hub) and semiconductor manufacturing (where we are one of the world's leading producers of chip manufacturing machinery).As a nation, we have the starting position needed to be equally successful where quantum technology is concerned: several of our research institutes are among the world's leaders in this field and have close ties with enterprises of all sizes. Now is the time to start building on that starting position.

However, like all revolutionary new technologies, quantum technology also raises ethical, legal and social questions. It is important not to lose sight of those questions. Security and privacy are currently topical issues, due to the fear that quantum computers will ultimately be able to break current types of data encryption. Although that danger certainly exists, we have two emerging technologies (post-quantum cryptography and QKD) with the potential to secure our data and our communications. The Netherlands can take the lead in promoting social debate regarding such ELSA issues, and thus put itself in a strong position within Europe and perhaps the wider world in relation to development of the necessary social, ethical and legal parameters. Various Dutch knowledge centres have already set the wheels in motion.

40 *See: www.tudelft.nl/2019/tu-delft/tu-delft-lanceert-publicatie-over-de-impact-van-quantuminternet/*

41 *See: www.pcworld.com/article/155984/worst_tech_predictions.html*



‘The Netherlands has enormous expertise in quantum technology and is therefore the focus of considerable international attention.’

04

THE DUTCH **QUANTUM LANDSCAPE** IN AN INTERNATIONAL CONTEXT

4.1 Braiding of government, science, industry and wider society

Quantum technology's successful development and innovative application will be extremely complex. Major scientific and technological challenges need to be overcome, and the integration of various technologies and disciplines will be necessary. That will require a great deal of thought, creativity and infrastructural provision, and impetus must be provided in the form of human capital and funding. Furthermore, quantum technology is conceptually complex and the translation of quantum concepts into practical applications is a challenge in itself. No person or organization - indeed no country - can develop the whole spectrum of quantum technology independently.

Continuous collaboration by the scientific community, the business community and government is required. What is required is not a linear process, in which the baton of responsibility is handed from runner to runner, but prolonged cooperation amongst the various parties playing concurrent roles at various stages.

In that context, the government must look beyond its traditional role as legislator and funding provider; the government must become a network partner and stakeholder, playing an active part in the innovation process. Furthermore, in contrast to what happens in most other fields, the business community will not only need to invest in high-TRL research[42] whose results can quickly be brought to market, but will also have to collaborate in fundamental research. Enterprises will additionally need to work with universities on the development of talent and the reinforcement of their own research capabilities.

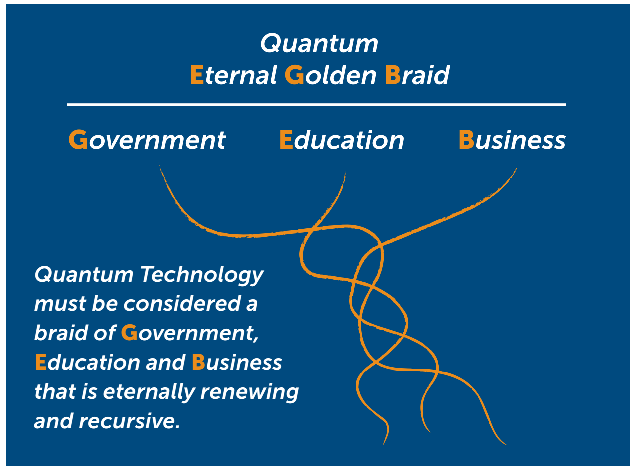


FIGURE 11
Innovation in science and technology is increasingly complex and requires continuous collaboration involving science, industry, government and society. Such collaboration is the basis of the 'golden triangle' approach used in the Netherlands for years in the so-called 'top sectors' and in mission-driven innovation policy. The variation on that approach illustrated here was put forward by a leading expert on quantum technology who was invited to make a keynote address during the open day in Utrecht on 16 April 2019, echoing the title of Douglas Hofstadter's famous book Gödel, Escher, Bach: An Eternal Golden Braid.

[42] *TRL stands for Technology Readiness Level. The higher a technology's TRL is, the closer that technology is to the industrial or social application.*

Such braiding of science, industry and government can provide unique opportunities for the Netherlands, because collaboration is integral to our culture, and we can draw on a long tradition of public-private partnership, which has repeatedly enabled us to secure a high position in the innovation rankings.

The Netherlands also has enormous expertise in quantum technology concentrated within a small geographical area. That attracts international attention, e.g. from large corporations keen to invest in the Netherlands. The environment that exists in the Netherlands facilitates the translation of scientific findings into applications and promotes business startups. It is very important that we now build on that base: the first quantum technology partnerships are springing up locally to form a Dutch quantum ecosystem. In the development of that ecosystem, the Netherlands will be aided by its capacity for 'system thinking': as a nation, we excel at systems engineering and combining highly complex technologies to form operational systems with unique capabilities. The Brainport region and the success of the Dutch semiconductor industry are prime examples. The knowledge acquired can be very useful in bringing about important breakthroughs in fields such as the quantum internet and quantum computers.

4.2 The Netherlands as 'Quantumland'

Despite being a small country, the Netherlands is well endowed with expertise and facilities in the field of quantum technology. The backbone of the nation's unique knowledge and innovation landscape is formed by three specialist research centres. From north to south, the three centres are QuSoft in Amsterdam, QuTech in Delft and QT/e in Eindhoven. Other important players are the universities of Leiden, Nijmegen, Utrecht, Twente and Groningen and the TNO and AMOLF research institutes. The various parties cooperate on research and innovation, not only with one another, but also with national and international enterprises.

According to a recent report by Birch, the Dutch knowledge institutions collectively have roughly 70 principal investigators (PIs) working on quantum technology, and in 2016 awarded nearly 2,500 MScs to students working in related fields.[43] Clearly, the Netherlands has an impressive pool of relevant expertise. Furthermore, the impact of the quantum technology research being done in the Netherlands is well above the international average, as the Elsevier report cited in subsection 1.2 attests.

4.2.1 The QuTech, QuSoft and QT/e research centres

QuTech: Advanced Research Center for Quantum Computing and Quantum Internet

QuTech is the Netherlands' biggest quantum technology research centre, with a strong international reputation. The centre was created in 2013 as a joint initiative by Delft University of Technology and TNO, supported partly by a public-private partnership with Microsoft and the Dutch Research Council. The centre's mission is to develop quantum technology based on superposition and entanglement, and to apply such technology in scalable quantum networks and quantum computers. In pursuit of that mission, the strengths of scientific research, technology development, engineering and industrial engagement are pooled. That multidisciplinary approach, combined with QuTech's interest in a 'full-stack' quantum computer and quantum internet, make the institute globally unique.

QuTech's research has four focus fields: fault-tolerant quantum computing, a quantum internet and network (quantum) computing, topological quantum computing, and quantum software and theory. QuTech additionally has a roadmap for shared development, providing for the development and sharing of cross-disciplinary technology. In 2014, QuTech was recognized as a National Icon. In 2018, the centre employed roughly 200 full-time personnel; the intention is to increase the staff to 350 FTEs by 2023.

QuTech has various successful partnerships with other institutes. The basis for the current success is the collaboration between Delft and Leiden, enabled by an FOM/NWO focus programme (2004-2013), an ERC Synergy Grant (2013-2019) and two Gravitation Programmes (one also involving QuSoft). QuTech is working with QT/e in Eindhoven to develop nanostructures for Majorana qubits, and with the University ofTwente on the manufacture of Si-MOS substrates. In partnership with LION in Leiden,

[43] Birch, 'Building a Q-Campus: realizing a quantum ecosystem in Delft', 2018.

QuTech: a National Icon

In 2014, QuTech was named by the Dutch government as one of the four National Icons, in recognition of its prominent position in the world of quantum research and its potential to help resolve major social challenges in fields such as health care and security. By giving QuTech National Icon status, the government highlighted the centre's importance to the Netherlands. In 2015, that led to public investment of roughly 150 million euros for ten years, via Delft University of Technology, TNO, the Dutch Research Council (NWO), the Ministry of Education, Culture and Science, and the Ministry of Economic Affairs.

QuTech is investigating the interaction of light and solids on the quantum scale, as well as hybrid applications of superconducting and topological quantum computing technologies.

QuTech has recently developed a quantum computing hardware and software platform: Quantum Inspire. The initiative means that quantum algorithms can be developed and testedwithin an emulation environment on SURF's national Cartesius supercomputer, which can emulate a quantum computer with up to thirty-seven qubits. The environment is available for use by the developers of quantum software and algorithms, and is intended to take quantum technology to the next level. A true quantum chip will shortly be added to the platform. For QuTech, the platform is therefore a fertile basis for open innovation, which can serve as a starting point for building a national quantum computing facility. Later in 2019, QuTech expects to be able to offer access to genuine qubits via the Quantum Inspire platform as well.

QuTech is also working with Microsoft to develop a quantum computer based on the so-called topological Majorana fermions. In 2012, researchers at Delft and Eindhoven universities of technology had an article published in Science, describing evidence for the existence of the hitherto hypothetical particles. The Microsoft Quantum Lab Delft was opened by King Willem-Alexander in February 2019.

In 2015, Intel invested fifty million dollars in an exclusive ten-year partnership with QuTech, aimed at developing the technology and electronics for quantum computing. Intel will be contributing expertise in the field of advanced qubit manufacture and relating to the production of electronics capable of working at very low temperatures.

QuTech is playing an international pioneering role in the development of a quantum internet. For example, the centre heads up the European Quantum Technologies Flagship's Quantum Internet Alliance, created to devise a blueprint for a European quantum internet. In that context too, QuTech has attracted private players. A quantum internet testing ground, interlinking various cities in the Netherlands' western conurbation, is being developed in partnership with KPN, ABN AMRO, AMS-IX, SURF and others. In the context of the European Flagship, QuTech is working with twelve companies, ranging from hardware developers (including Toptica of Germany and Janssen Precision Engineering of the Netherlands) to application developers (such as SAP).

In 2019, industrial companies contributed a total of more than ten million euros to QuTech's research.

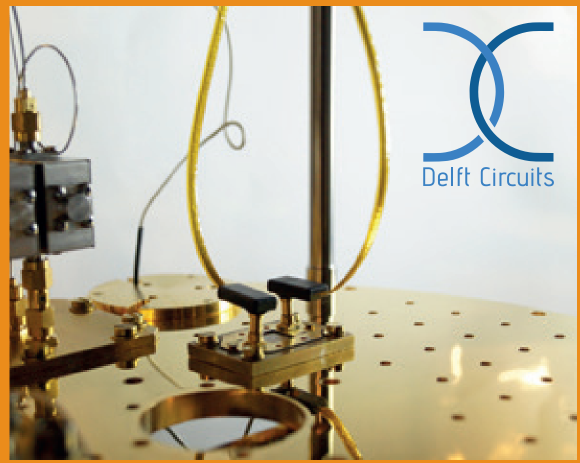
Delft Q-Campus

Microsoft's announcement of plans to set up its own lab on the Delft campus has led to establishment of the Q-Campus[44], an initiative intended to extend the local QuTech ecosystem with companies, startups and shared facilities. The Q-Campus organization, whose main tasks will be acquisition, account management and community building, is currently taking shape. More recently, the Finnish company Bluefors announced that it would be opening a research facility on the Q-Campus and a handful of startups are now on site as well. For example, Single Quantum has been marketing superconducting single-photon detectors since 2012, while Delft Circuits has been commercially producing broadband microwave cables for cryogenic environments since 2017 and QBlox has been making hardware for controlling and reading multi-qubit systems since 2019. In its previously cited study, Birch Consultants forecasts that the Q-Campus

[44] For the moment, this is merely a working title.

Example of a startup: Delft Circuits

Active since 2017, Delft Circuits is a startup whose roots lie in the Quantum Nanoscience department at Delft University of Technology. The company develops qubit control cables for inside and outside cryostats. It is a niche market, in which only a handful of manufacturers currently operate. The company's first product, Cri/oFlex®, is a low-thermal-load, flexible type of RF cable, which is massively scalable. Delft Circuits now employs about twelve people from a variety of backgrounds.



community could grow to 900 entrepreneurs and researchers by 2023, 350 of them at QuTech itself.

Quantum Applications South Holland Fieldlab
Recently, partnerships relating to applications and use cases in the field of quantum computing and a quantum internet have been established on the basis of regional collaboration (QuTech, TUD, TNO, IQ) and alignment with prospective public and private-sector users. In the context of the National Agenda for Quantum Technology, the initiative is closely associated with the other application-oriented activities in the Netherlands, such as those in Amsterdam and Leiden (see the descriptions presented later in this document).

The value of quantum technology for various sectors is being tested and evaluated in association with the project partners by developing suitable models and translating them into software and algorithms. The approach is based on the use of hardware and simulators made by QuTech (Quantum Inspire, Quantum Link) and the other relevant suppliers around the world. The initiative is intended to expedite the further development of use cases, to accelerate the uptake of quantum technology by the Dutch business community, and to secure alignment with relevant hardware suppliers. The focus application areas addressed so far are water (see QuantumLab in 3.2.4), finance and energy; meanwhile, exploratory assays are being made for security and bio/pharma.

QuSoft: Research Centre for Quantum Software
QuSoft is a partnership involving CWI, the University of Amsterdam and Vrije Universiteit Amsterdam. Having begun in 2015, the centre's mission is to develop new protocols, algorithms and applications suitable for small to medium-sized quantum computing prototypes. The world-leading research undertaken at the centre follows four pathways: quantum simulation and applications for systems with a small number of qubits, quantum information science, cryptography in a quantum world, and quantum algorithms and complexity. In 2018, QuSoft had 60 full-time personnel; the institute hopes to have a workforce of 120 FTEs by 2022.

Various partnerships ensure that QuSoft has close relations with the rest of the quantum landscape. Within the Quantum Software Consortium, for example, QuSoft collaborates with QuTech and Leiden University on the development of quantum software and applications. Individual QuSoft researchers also collaborate closely with colleagues at other Dutch institutions. That is the case with the quantum simulator work for the new Physics Open Competition Grant funded by the Dutch Research Council. Therein, QuSoft is working with Utrecht University, Radboud University and Eindhoven's QT/e. Similar collaboration is taking place within the iqClock Programme for ultra-accurate atomic clocks.

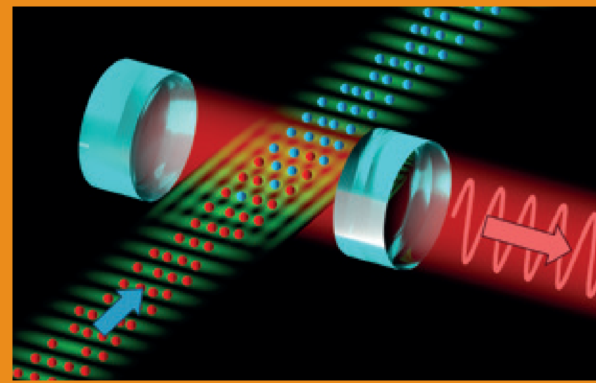
QuSoft works closely with various industrial partners. In February 2019, QuSoft started a unique collaboration with Bosch Group, which involves a two-year exploration of the practical applications of quantum computing within Bosch, particularly for engineering developments and in the fields of artificial intelligence and machine learning. QuSoft also works with ATOS on quantum programming workshops. Alongside those activities, QuSoft has linked up with ABN AMRO to start a project on quantum-safe banking. Meanwhile, plans are taking shape for the launch of a spinoff company, which will offer quantum software products and services.

Quantum Application and Software Hub Amsterdam
As companies and public bodies become more aware of the potential impact of quantum technology, there is increasing interest in exploring use cases and quantum

The iqClock European Quantum Flagship project

In partnership with MoSaiQ training for young researchers, the iqClock Quantum Flagship is directing the industrial development of an integrated optical matrix clock. One strand of the work involves the development of a new type of optical clock: the super-radiating clock, which utilizes a continuous source of ultra-high-intensity cold atoms, making it much more accurate than existing atomic clocks. Together, the various research activities taking place around the country form a basis for the development of optical atomic clocks, with LioniX International, the University of Twente and ESA joining forces to develop new, simplified laser systems, for example, but also to do research into quantum computers and quantum simulators based on ultra-cold atoms.

The results have potential applications in sectors such as telecoms and security. (Illustration: Florian Schreck and Shayne Bennetts, University of Amsterdam.)



technology applications in an increasingly wide range of application areas.

The Quantum Application and Software Hub Amsterdam is being set up to service the growing demand for such research. At the Hub, challenges presented by the business community will be addressed by allying QuSoft's quantum software and application-related expertise to the application-specific knowledge that exists within the universities in fields such as business and finance. The Hub will also serve as a medium for local and regional governments to facilitate collaboration, and both Innovation Exchange Amsterdam (IXA) and the Amsterdam Science Park (ASP) are involved to support the development of new ideas, solutions, products and services, and to expedite the process of bringing innovations to market.

The Hub will work with commercial partners in various fields, including quantum finance (since the financial services industry sector in Amsterdam has a natural ecosystem), quantum chemistry and material development, or, for example, quantum applications in operations research. As well as being scientifically interesting, those fields have direct tie-ins with applications and the business community.

To begin with, most analyses can be performed on a platform-independent basis. However, implementation on hardware will be necessary at a later stage. The focus may be on quantum simulators or quantum computers, or indeed on quantum communication infrastructure or quantum sensors. To a significant extent, the success of the Hub will therefore depend on a willingness to collaborate with all players in the Quantum Delta NL and with players beyond. By being prominent and playing a bridging role, the Hub will be able to win the support for the National Agenda for Quantum Technology from additional actors in the Netherlands and other countries. Thus, the Hub will reinforce the QΔNL and contribute to an attractive investment climate.

QT/e: Center for Quantum Materials and Technology Eindhoven
QT/e began in 2018 as a joint initiative by the faculties of Technical Physics, Mathematics & Informatics, and Electrical Engineering at Eindhoven University of Technology. QT/e focuses on pioneering fundamental and applied research, with a view to enabling breakthroughs in the development of quantum materials and quantum technology, leading to the development of new products and methods that are of benefit to society. Forty researchers from various departments are working on quantum simulation, post-quantum cryptography, quantum protocols, quantum nanophotonics, and quantum materials and devices.

QT/e and QuTech are working closely together to realize complex structures at the nano-scale for topological quantum computing applications based on Majorana particles. QT/e and the University of Twente are doing development work on quantum-secure authentication, while QT/e is additionally involved in the development of integrated technology to enable QKD-on-a-chip as part of the European UNIQORN

Quantum-secure authentication

QT/e researchers are working on the theory of quantum-secure authentication (QSA), utilizing 'physically unclonable functions' (PUFs). Directing a very weak laser beam at a complex diffuser reveals a unique pattern that can be used for authentication. In collaboration with QT/e, a team at the University of Twente has built a QSA-in-a-box demonstrator (see photo). The intention is to miniaturize the technology in due course, with the ultimate dream of creating a quantum credit card.

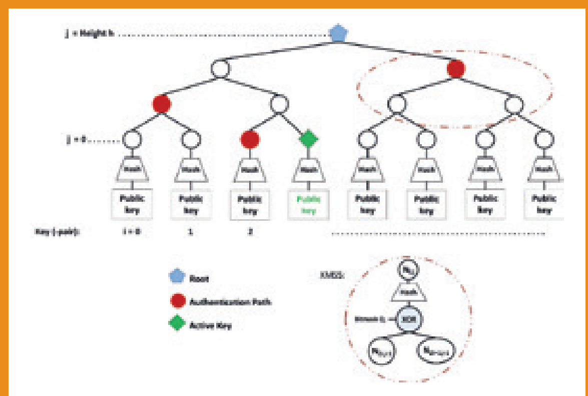
project[45]. Through the various programmes, Eindhoven's expertise in the fields of nanotechnology, materials science and integrated photonics is being applied to quantum technology. Controlling cold atoms for quantum simulation purposes is one of the main focuses at Eindhoven University of Technology's Cold Atom Lab. In partnership with QuSoft, the University of Amsterdam, Utrecht University and Radboud University, the Eindhoven team is involved in an NWO programme aimed at simulating quantum materials using cold atoms and molecules.

Another focus area for QT/e is post-quantum cryptography: researchers are looking to develop and implement the technology, while also performing security analyses and investigating side-channel attacks on post-quantum cryptosystems. The systems involved are designed to withstand attacks by quantum computers. Quantum cryptanalysis, including the development of new quantum cryptanalysis algorithms, is an integral feature of the security analysis work and provides a direct link between QT/e and QuSoft. Only twenty-six algorithms now remain in the NIST competition to find a post-quantum cryptography standard, and six of them are strong candidates put forward by QT/e. Some of the candidate algorithms were developed in partnership with Cisco, IBM, NXP, Philips and others.

In addition, Microsoft and QT/e have recently linked up with a view to moving forward the development of Majorana transmission within topological materials. The alliance provides for the funding of multiple junior research posts. The high-tech systems and materials top sector is also involved. Under the UNIQORN umbrella, QT/e is working with various partners, including Eindhoven-based Smart Photonics. QT/e's High Capacity Optical Transmissions

Future-proof update security

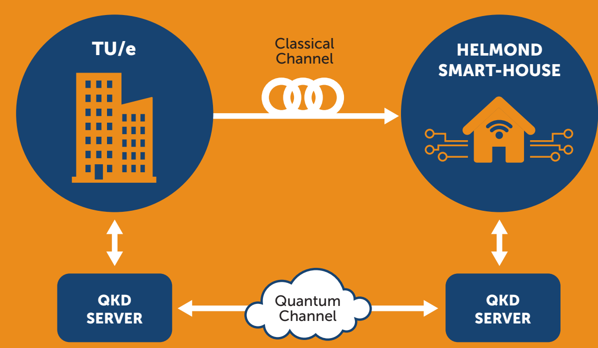
Software updates depend on the authenticity and integrity of the patches provided. If a cybercriminal were able to compromise the update security, it would be possible to infect all computers that downloaded the attacker's fake patch. At the moment, updates are secured using electronic signatures. Against that background, QT/e has taken the initiative with the design and standardization of XMSS, a new electronic signature system that is able to resist quantum computer attacks. XMSS is now an IETF standard and looks set to become a NIST and ISO standard before long[46]. It is already being used for QRL (a new cryptocurrency), for example.



[45] *See https://quantum-uniqorn.eu*
[46] *See https://csrc.nist.gov/projects/stateful-hash-based-signatures*

Quantum-securely interconnected smart homes in the Brainport Smart District

In the town of Helmond, the Brainport Smart District is being developed. For one of the first projects in the district, Eindhoven University of Technology's CASA student team is building a new type of home, which has to be affordable, comfortable and sustainable. The home will serve as a testing and development setting for the very latest data and domotics technologies. The data generated needs to be securely accessible from anywhere. A quantum-secure connection is therefore being realized between the home in Helmond and the university campus. Quantum keys will be used to secure the transmitted data. A second quantum-secure connection will be set up with Waalre town hall. The project partners include domotics supplier BeNext BV, network provider KT Waalre, SURF and the Municipality of Waalre.



Lab is developing a testbed for the quantum-secure interconnection of smart homes within the Brainport Smart District in Helmond. The Eindhoven lab is testing the technologies already available and additionally testing the integration of technologies.

Like quantum technology, photonics and integrated photonics are recognized as key technologies. New technology for communication systems, data security and innovative sensors all feature prominently on the National Photonics Agenda and in the plans for creation of a strong integrated photonics ecosystem in the Netherlands. In view of the level of shared expertise in both (integrated) photonics and quantum technology in Delft, Eindhoven, Nijmegen and Twente, it is plausible that a large ecosystem will develop at the interface between those key technologies. The European UNIQORN project and the Brainport Smart District's quantum-secure connected home are in the vanguard of that development, along with the quantum internet research being done in Delft.

4.2.2 Dutch knowledge institutions and universities

As well as the backbone formed by QuTech, QuSoft and QT/e, the Netherlands has an extensive 'nervous system' of universities and institutes busy developing quantum technology.

TNO Over the last four years, TNO has significantly increased its quantum technology activities, which have now acquired a critical mass and a significant profile within the landscape. TNO's Quantum Technology Expertise Group is fully focused on quantum technology. Its mission is to move forward the development of this groundbreaking technology and promote its availability, and to realize applications in various other markets such as defence, ICT and space travel. Through QuTech, the department is working on the development of quantum computers and the quantum internet, as well as the development and application of quantum sensors. Several other TNO expertise groups - Radar Technology, Acoustics & Sonar, Distributed Sensor Systems, Optics, Optomechatronics, Space Systems Engineering, Nano Instrumentation, Cyber Security & Robustness, Networks and Strategic Business Analysis - are also involved in the institute's quantum technology activities. For example, the Optics Group is working on the development of quantum photonic integrated circuits in partnership with PhotonDelta, while the Cyber Security & Robustness Group is researching applications for quantum computing and quantum communication, as well as the transition to post-quantum cryptography. TNO is additionally active in the field of nano-manufacturing. In all its focus domains, TNO operates in partnership with the private sector. In total, scores of TNO staff are directly or indirectly involved with quantum technology.

CWI has been doing fundamental work on quantum computing, quantum communication and cryptography in a quantum world since the 1990s. Various groups are active in this field, and the CWI complex is where QuSoft is based. CWI contributed to the first communication protocol that demonstrated that quantum communication could be more efficient than classical communication. The institute was also responsible for developing one of the first quantum algorithms, employing a widely used technique to enable reasoning about quantum algorithms. Another line of work involves quantum cryptographic protocols and post-quantum cryptography based on both classical protocols and quantum protocols. Strong ties also exist with classical optimization and classical complexity theory, which form the starting point for the development of new quantum applications in industry.

AMOLF is an NWO institute, based on the Amsterdam Science Park. The institute's Photonics Forces Group is working on quantum nano-photonics, where light and matter interact strongly on a nano-scale. The group is working on the development of completely new detection methods in photonic optomechanical systems. One of the aims is to use such systems to accurately determine the quantum status of small mechanical objects. On the various initiatives, the group collaborates with both Delft University of Technology and QT/e.

Delft University of Technology Various research teams within a number of faculties at Delft are involved in the development of quantum technology. The Quantum Nanoscience Department within Delft's Kavli Institute of Nanoscience has fifteen principal investigators studying and visualizing the quantum effects that occur within materials, with a view to utilizing and managing their capabilities in a controlled manner. It is also the intention to develop devices that harness the potential of those effects, thus yielding social impact. The work involves themes not covered by the QuTech roadmaps, such as quantum sensors, new quantum materials and fundamental research for qubits. The university's Faculty of Electrical Engineering, Mathematics and Informatics has a Quantum Engineering Department that is looking at the architectures and software needed for quantum computing and for translation between classical ICT and quantum systems. The team is focusing on the technical challenges associated with upscaling the architecture of quantum computers and the quantum internet, CryoCMOS, 3D connections, quantum software and quantum information theory. Meanwhile, the Software Technology Department is investigating how a quantum computer and a quantum internet could be programmed and tested. Finally, the Department of the Philosophy and Ethics of Technology within the Faculty of Technology, Control and Management (TBM) is researching the social impact and acceptance of quantum technology. That work is being done in partnership with the Faculty of Industrial Design. Under the supervision of TBM and in collaboration with QuTech, Delft University of Technology published a magazine in June describing the social impact of the quantum internet.[47]

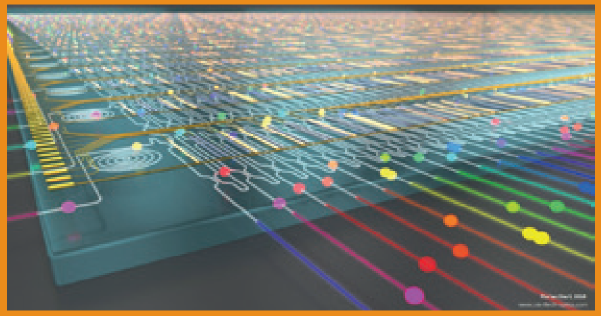
Leiden University In Leiden, research into quantum applications is being done on the aQa (applied Quantum algorithms) platform, a forum for collaboration between the Leiden Institute of Physics (LION) and the Leiden Institute of Advanced Computer Science (LIACS). In partnership with QuTech, LION is investigating the interaction of light and matter at the quantum scale, as well as hybrid applications of superconducting and topological quantum computing technologies. Another team is working on ultra-microscopy, where various techniques are used to characterize materials on the atomic and quantum levels. Leiden is additionally involved in the Quantum Software Consortium, within which it coordinates the theme of Cryptography in a Quantum World. Fifteen principal investigators are active at Leiden in those various fields. Leiden also offers a two-year MSc programme entitled Research in Physics, Quantum Matter and Optics.

University of Amsterdam In Amsterdam, quantum technology is an important focus area within the Quantum Matter and Quantum Information research theme. The university's participation in QuSoft is linked to that theme. Multiple research teams are clustered around that focus area. Some are engaged in experimental work (Quantum Gases and Quantum Information, Quantum Electron Matter) and some in theoretical work (Condensed Matter Theory and Algebra, Geometry and Mathematical Physics). More than thirty principal investigators are involved, many of them working within QuSoft.

[47] *See https://issuu.com/tudelft-mediasolutions/docs/quantum_magazine_june_2019*

Example of a startup: QuiX

Enschede-based QuiX is a spinoff from the University of Twente. The company intends to build the first quantum photonic processor, which it expects to complete in one to two years. In pursuit of that goal, QuiX is collaborating closely with PhiX, another UT spinoff, which claims to be the first manufacturer capable of the automated production of photonic chips. The partnership exemplifies the close relationship between the worlds of quantum technology and integrated photonics. The illustration is an artist's impression of a photonic processor, in which light quanta interfere within a complex optical switch (illustration by Florian Sterl for the University of Twente).



Amsterdam coordinates the iqClock Quantum Flagship project, as well as a recent NWO programme on quantum simulation, in which Utrecht University, Eindhoven University of Technology and Radboud University are all involved.

University of Twente In Twente, quantum technology is being developed and studied by the Quantum Transport in Matter (QTM) team, the Complex Photonic Systems (COPS) team and the Laser Physics and Nonlinear Optics (LPNO) team. In addition, the behaviour of individual spin qubits in silicon is being studied by the NanoElectronics (NE) team. Within the QTM research field, one of the main topics is superconducting, topological materials for Majorana physics and quantum computing applications. That team is working with quantum dots and superconducting nanofilaments, in partnership with QuTech and QT/e. Having demonstrated quantum-secure authentication, COPS is now working on the combination of physically unclonable keys with quantum communication protocols. Along with LPNO, COPS is working on ways of performing quantum calculations on the basis of integrated photonic systems. In 2018, researchers at Twente developed a photonically integrated system of 8X8 universal, programmable gates for the implementation of quantum information protocols. On the basis of that breakthrough, the university linked up with LioniX International to form a company called QuiX, with the aim of building the world's biggest quantum photonic processor. The University of Twente has about ten principal investigators working on themes associated with quantum technology.

Radboud University In Nijmegen, quantum materials research is carried out within the Institute for Molecules and Materials (IMM), where use of the High Field Magnet Laboratory (HFML) is a central feature of the Spectroscopy of Quantum Materials theme. The primary foci of the research are the behaviour of correlated electron systems within materials under the influence of extreme magnetic fields and ultra-fast interactions between light and magnetic materials. Of the twenty PIs concerned with this theme, about half are working on quantum technology. Quantum chemistry research is undertaken at the Radboud University as well, and the university participates in the NWO cold atoms and molecules programme, along with the University of Amsterdam, Utrecht University and Eindhoven University of Technology. In addition, the Digital Security Group within the Institute for Computing and Information Sciences (iCIS) is active in the field of post-quantum cryptography. The group is closely involved with the NIST PQC project, for example. It is also participating in the experiments Google is organizing with a view to developing post-quantum TLS security protocols. One such experiment carried out in 2016 involved the NewHope algorithm, which Radboud University helped to develop. In 2019, Google and Cloudflare announced a new round of experiments with the NTRU-HRSS and SIKE algorithms, again co-developed by Radboud University.

Utrecht University In Utrecht, more than ten theoretical and experimental principal investigators are studying quantum phenomena and their applications. There is very strong interaction between the theoretical and experimental domains with regard to quantum materials, cold atoms and quantum simulation; the research contributes to the understanding of phenomena such as spintronics, superconduction, quantum magnetism, topological quantum states and quantum computing, as well as to the development of new quantum materials. For example, Utrecht is participating in the NWO cold atoms and molecules programme, together with the University of Amsterdam, Eindhoven University of Technology and Radboud University, and Utrecht is overseeing an NWO spintronics programme. The introduction of research hubs on themes such as energy, health and sustainability has created an excellent opportunity for aligning quantum research with the wishes and requirements of potential end users.

University of Groningen The Quantum Devices (QD) team is engaged in fundamental research into quantum coherent dynamics in solid-state devices (including organic molecules and semiconductors). The work has clear links to spintronics and quantum information applications, as illustrated by the recent experimental realization of a quantum state ('bit') at wavelengths within the telecommunications range. The Physics of Nano-systems team and the Spintronics and Magneto-optics of Nanomaterials team (each with one PI) are studying the interaction between the quantum mechanical degrees of freedom 'spin', 'charge', 'valley-chirality' and 'photon chirality' in new 2D materials and their heterostructures.

4.3 The global playing field

Although the Netherlands occupies a unique position, it is only one player in a major international push to develop quantum technologies, with Europe, North America and China to the fore. The quantum technology work being done in each of those regions is outlined below.

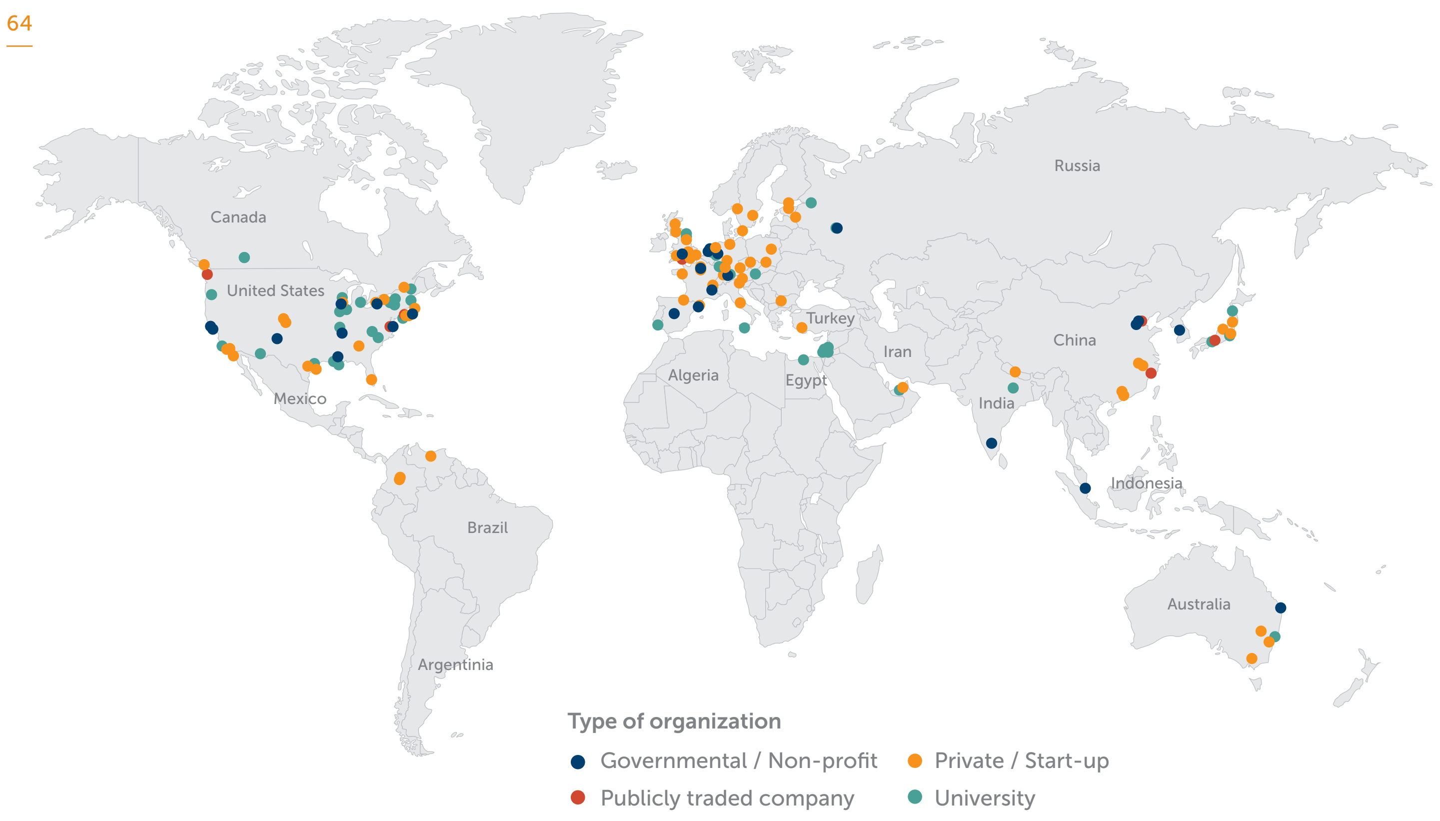


FIGURE 12
North America, Europe, Japan and China are the hotspots for quantum technology. (Source: Innovatie Attaché Netwerk; data: Quantum Computing Report, situation in August 2019).

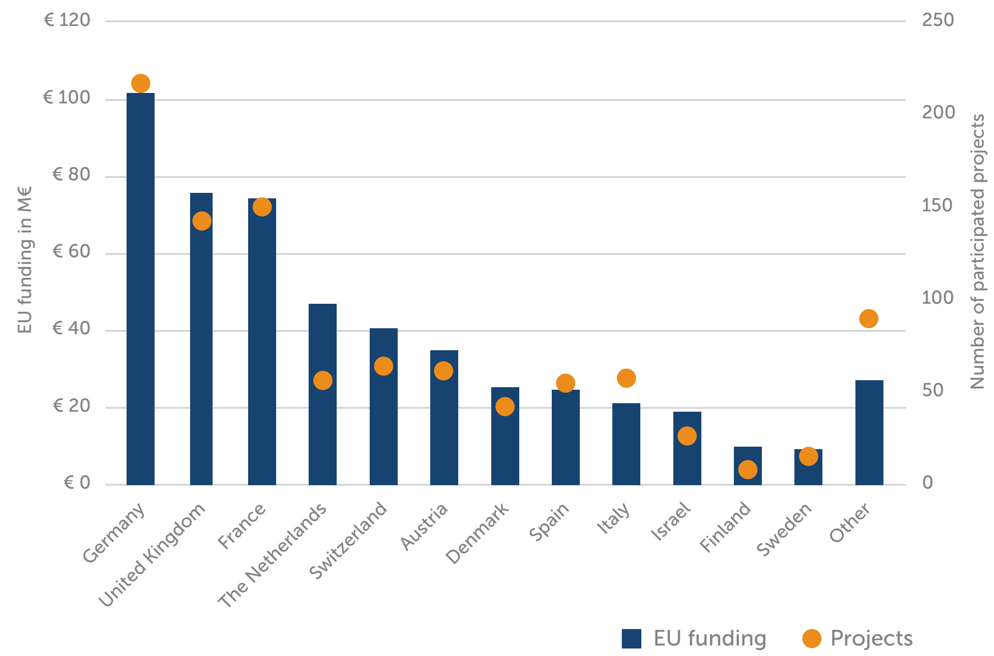


FIGURE 13
European quantum technology funding, by country. (Source: Birch)

4.3.1 Developments in Europe

European scientists were very influential in the emergence of quantum mechanics in the early twentieth century; in recent decades, the region has also played a leading role in the further development of quantum technology. Established in November 2016, ERA-Net QuantERA has made several calls for proposals, with a view to funding projects with an emphasis on fundamental quantum technology research. The first call, in 2017, to which the Dutch Research Council contributed 1 million euros, led to the funding of nine projects with Dutch involvement. The exercise was an unprecedented success, with a high return on investment.

Following publication of the Quantum Manifesto in 2016, the European Union launched a Quantum Technologies Flagship programme in 2017. With a budget of a billion euros, the programme is intended to promote public-private collaboration in Europe, and to establish the region as the world's leading centre for quantum technology development. In 2018, twenty projects were awarded grants totalling 132 million euros. Developments in quantum technology are also funded from other EU sources, including the European Research Council (ERC). In relative terms, the Netherlands does well in these EU programmes, as Figure 13 shows.

In addition to the quantum technology funding by the EU, various individual member states, including France, Sweden and Switzerland, have their own programmes. Two national programmes warrant particular attention, one because of its pioneering role (UK) and one because its objectives are closely aligned with this Agenda (Germany).

United Kingdom The UK is one of the first European countries to invest in a coherent, national programme for quantum technology. In autumn 2013, the British government announced an investment of 270 million pounds (more than 300 million euros) over five years, with the emphasis on translating quantum technology to the market, promoting enterprise and boosting social impact. Cooperation among universities, enterprises and government bodies was encouraged, and the first funds were released at the start of 2015. The programme was therefore one of the first where the translation of quantum technology to industry (and wider society) was a primary objective, rather than solely investment in fundamental research.

A feature of the programme was the formation of four Quantum Hubs, one for sensors and metrology, one for quantum-based imaging technology, one for networked quantum computing applications, and one for quantum information networks. Further investment in the hubs was announced at the end of 2018: an initial 80 million pounds (93 million euros), followed by a second tranche of 235 million pounds (273 million euros) for continuation and expansion of the national programme. Enabling technologies and education were among the fields targeted for investment.

Another significant feature of the programme was consultation with all sectors of the community regarding the social and ethical implications of quantum technology. One recent product of that consultative approach was the 2018 Quantum Technologies Public Dialogue Report, commissioned by the British Engineering and Physical Sciences Research Council (EPSRC).

Germany As well as being one of the central players in the Quantum Flagship programme, Germany is investing 650 million euros in its own national programme. With six lines of action, the German programme is intended to reinforce and promote cohesion in the academic world, to develop new technologies for the market, to encourage international collaboration, and to expedite social acceptance and adoption of quantum technology. The main topics addressed are the quantum computer, quantum communication, quantum sensors and basic technologies for quantum systems. Germany's programme therefore has clear parallels with the themes and focuses of our own National Agenda.

The interest in quantum computing and artificial intelligence is further illustrated by the funding of about a hundred research posts at the Forschungszentrum Jülich, where a programme with a budget of 36 million euros has been started to investigate quantum and neuromorphic computing: a promising combination of technologies for applications such as quantum machine learning.

4.3.2 Developments in Canada and the United States

Canada Over the last ten years, the Canadian government has invested 1 billion Canadian dollars (about 660 million euros) in quantum technology research and development. A particular hotspot for quantum technology is the city of Waterloo, whose university campus is home to the Institute for Quantum Computing, the Perimeter Institute for Theoretical Physics and the Mike & Ophelia Lazaridis Quantum Nano Centre, where research into quantum information and quantum computing is concentrated, with nearly four hundred researchers active. The area also has infrastructure and lab facilities, training institutes for tech-entrepreneurship and Quantum Valley Investment (QVI). Consequently, Waterloo's Quantum Valley serves as a blueprint for a quantum technology ecosystem. Early in 2019, IBM announced that Waterloo would be the only Canadian university to act as an IBM Q-Network partner.

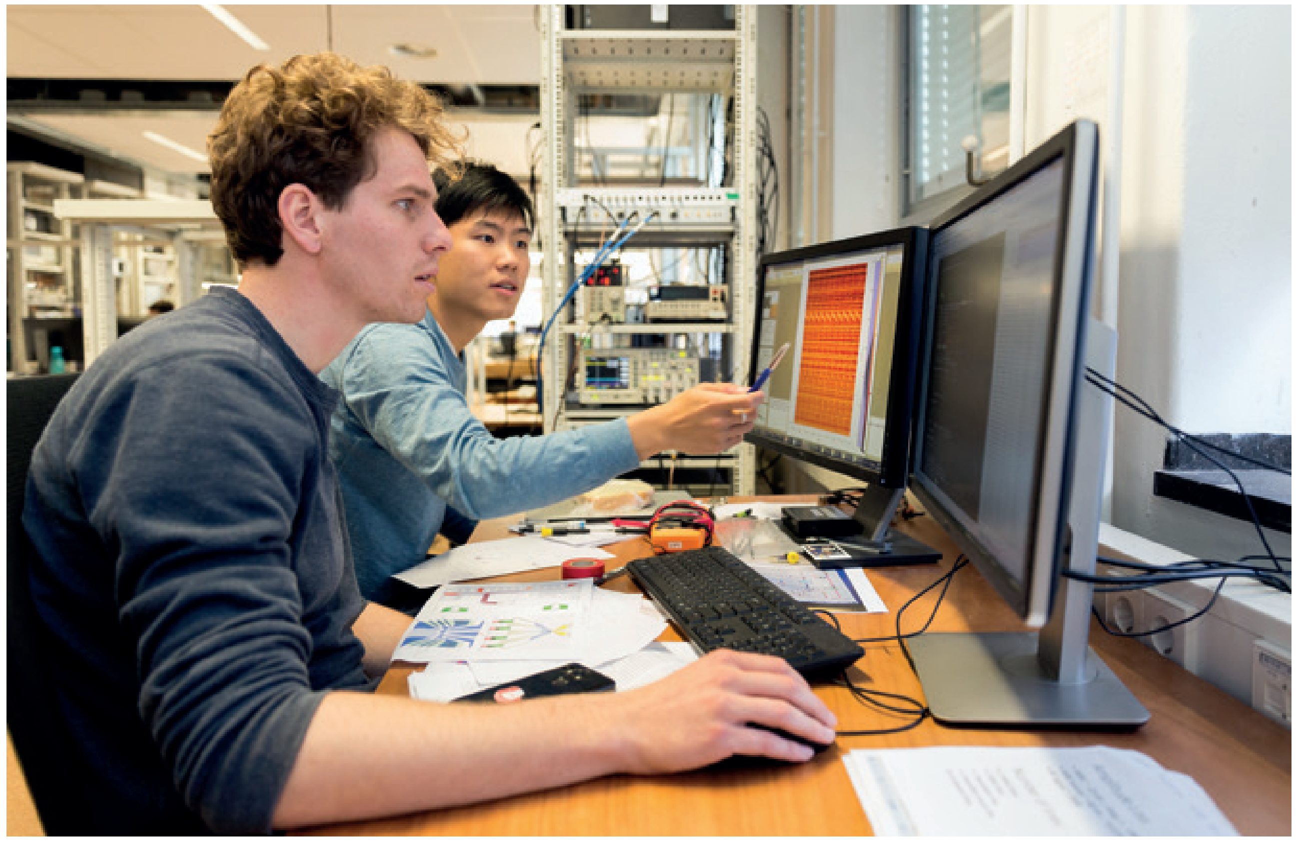
Through QVI, private investors can contribute to quantum technology research and development. Unusually, researchers funded through QVI will retain the rights to their results and their commercial exploitation. Waterloo University has seeded more than 160 startups, a rapidly increasing proportion of which are working on quantum technology. Canada is consequently fifth in the global rankings for patent applications relating to quantum computing. Strong ties exist between the work being done in Canada and the research at QuSoft and the CWI.

United States Scores of prominent universities and institutes in the US are working on quantum technology. However, the idea of a Quantum Hub or ecosystem has not gained traction. It is therefore interesting that, in November 2018, the Senate passed the National Quantum Initiative Act, which provided for 1.2 billion dollars (more than 1 billion euros) of existing funding to be allocated to research relating to quantum information and quantum communication. NIST and NASA have been assigned an advisory role in the funding plan, while NIST and NSF are tasked with setting up standardization and research programmes, and NSF and the Department of Energy have been given responsibility for creating a number of Quantum Hubs. IARPA, DARPA and ARO – organizations within the US national intelligence service and Ministry of Defense – also play important roles in quantum technology research.

Many of the companies active in the development of the quantum computer and quantum information technology are North American, including 1Qbit, Atom Computing, D-Wave, Google, Honeywell, HP, HRL Labs, IBM, Intel, ionQ, Lockheed-Martin, Microsoft, Northrop Grumman, Raytheon and Rigetti. Such companies have large-scale national and international collaborative arrangements with knowledge institutions, including QuTech and QT/e; indeed, QuTech has also received support from IARPA.

4.3.3 Developments in China

In recent years, China has unveiled some notable achievements with quantum technology. For example, researchers at the Chinese Academy of Sciences developed the Micius quantum experimentation satellite within the space of ten years. The satellite was launched in 2016. Before long, an entanglement was realized between the ground station and the satellite, across a distance of 1,400 kilometres. In a collaboration with the University of Graz, the satellite was used in 2018 to send a QKD-encrypted signal across



a distance of more than 7,600 kilometres. That remains a world record for quantum signal transmission. Micius also forms part of the quantum connection between Beijing, Shanghai, Jinan and Hefei (which also has the world's longest underground fibre-optic quantum network).

In addition, China is striving to build the world's first quantum computer. In pursuit of that goal, the National Laboratory for Quantum Information Sciences is to be built near Hefei at a cost of 10 billion US dollars. Various Chinese companies are active in the quantum technology domain as well. In 2015, Aliyun (the cloud computing arm of the Alibaba Group) and the Chinese Academy of Sciences announced joint plans to build the Alibaba Quantum Computing Laboratory in Shanghai. In February 2018, the first cloud-based quantum computer service was unveiled. With an eleven-qubit system at the same laboratory as its basis, the service was then the second most powerful quantum computer service in the world, after IBM's.

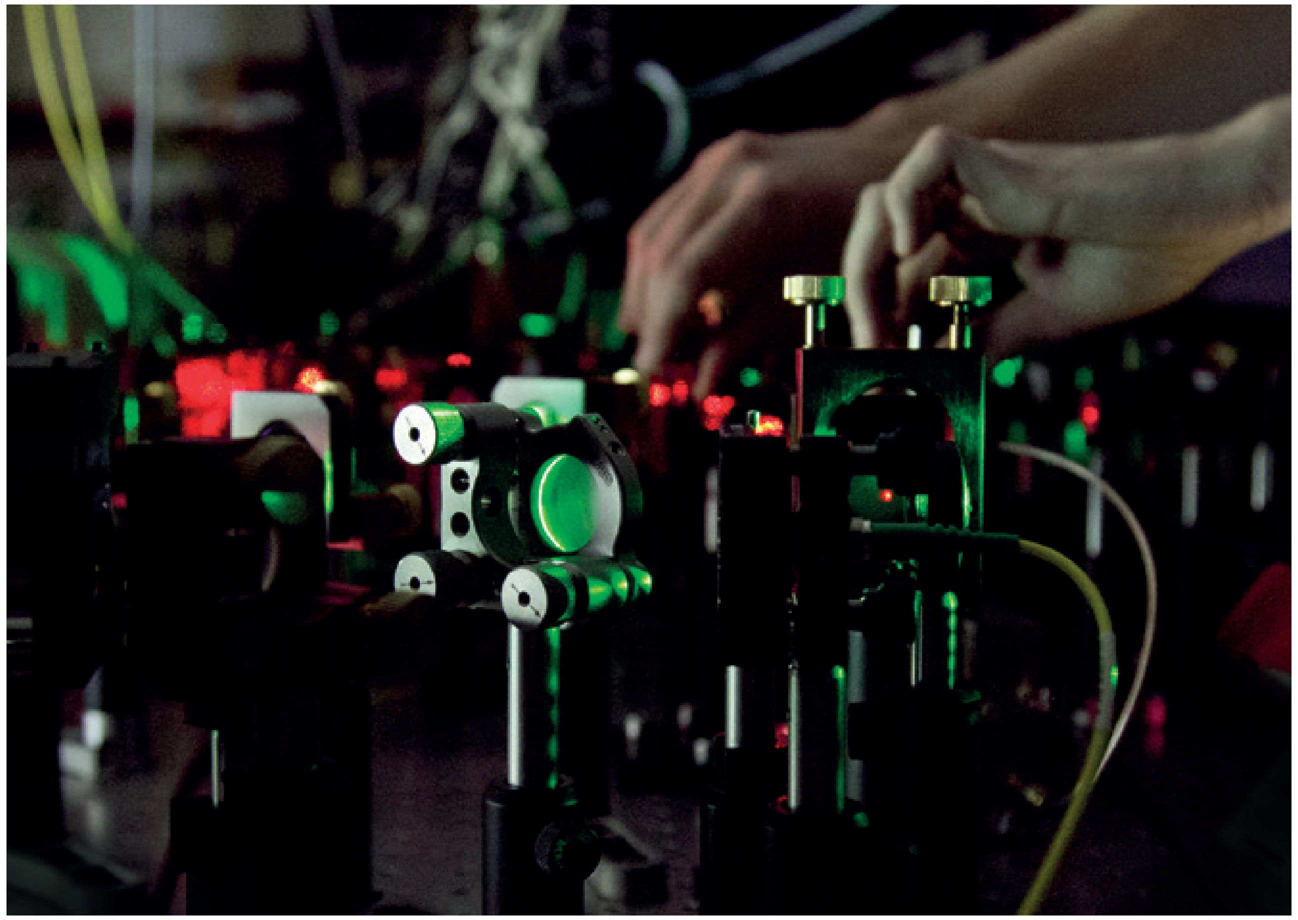
4.4 The balance between national strength and international collaboration

The Netherlands is an important player in the international quantum technology field; years of investment in research and development have provided the country with a strong knowledge and innovation basis. The Netherlands is a leader in the fields of quantum computing, quantum communication and quantum simulation, as well as the development of associated applications and protocols for data security and other matters. At the moment, the seeds are being sown for increased collaboration between academia and industry, the development of prototypes and the first concrete quantum products and services, startups and spinoffs, and a national innovation ecosystem.

Of course, the Netherlands is not alone in pursuing such policies; around the world, billions are being invested both through coordinated continental scale programmes (EU, US and Canada, China) and by individual countries (e.g. the UK, Germany and France). In one sense, that implies greater competition, not only to secure external investment, from large internationally active corporations and other sources, but also to attract and retain talent. However, quantum technology's implications for the security and welfare of our society depend to a significant extent on where the technology is first developed to maturity. The development of quantum technology in a democratic setting therefore has to entail collaboration, even if only to secure agreement regarding the responsible use of quantum technology.

Global investment also creates opportunities: quantum technology is extremely complex and its full development will require a great deal of time, expertise, infrastructure and material resources. Even a country or bloc as large as the US or the EU is unlikely to be able to take all forms of quantum technology independently from their current, relatively basic levels to full commercial and social introduction. Hence, players all around the world will need to rely on one another and, to some degree, to work together by sharing results, sharing and building up infrastructure, bringing through talent and building up a workforce of quantum engineers to help integrate quantum technology within society.

This Agenda therefore seeks to strike an appropriate balance between, on the one hand, the need to reinforce our national strengths in quantum technology, and to make the Netherlands as (internationally) attractive as possible for investment and as a base for internationally active institutes and enterprises, and, on the other hand, the need to increase the scope for international collaboration and knowledge-sharing as a means of boosting expertise and skill in the Netherlands. Those dual objectives are pursued by, on the one hand, investing in lines of activity and national catalyst programmes, and, on the other hand, by forging bilateral and multilateral partnerships, e.g. with Japan, Canada and the US, and by lobbying more actively for national quantum activities, e.g. in Brussels.

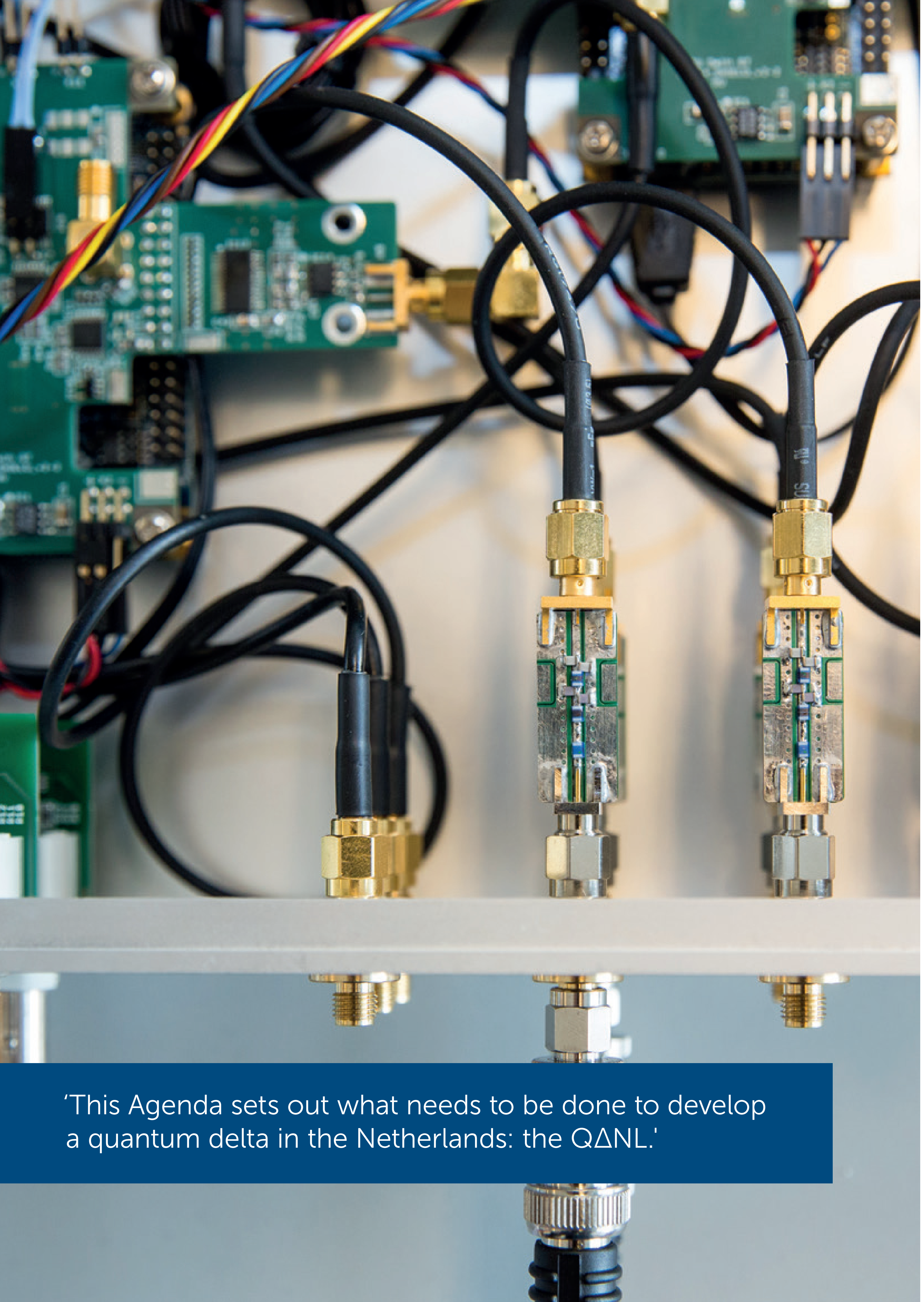


4.5 Conclusion

The geographical concentration of the Netherlands' quantum technology expertise and facilities sets the country apart on the global stage. Furthermore, that concentration is reinforced by the Dutch culture of cooperation. The Netherlands is very strong in systems engineering and in combining technologies to form operational systems: fields that are vital for innovation. The country is therefore attractive to international companies willing to invest heavily in developing the quantum technology of the future. Meanwhile, at the local level, we are also seeing the first startups making commercial use of quantum technology. Our melting pot of knowledge, technology, industry and enterprise is creating growth centres, around which an ecosystem is starting to form. That represents an opportunity that must be seized. On the basis of this Agenda, we are therefore investing in the reinforcement of our nation's scientific basis, in the creation of technology-driven market opportunities, in building up and extending a national ecosystem, in education, and in securing a leading position in the social dialogue about quantum technology. As explained in Section 5, a number of action lines and national catalyst programmes have been defined as a means of channelling our strengths.

The development of quantum technology is an international undertaking. The investment necessary and the complexity of the scientific and technological advances required are such that no nation is capable of developing the technology in isolation. Against that background, countries everywhere are investing heavily in quantum technology: the EU is investing a billion euros in the Quantum Flagship, while individual member states are ploughing hundreds of millions into national programmes. The US is investing more than a billion euros, and China is also allocating huge resources to quantum technology. Heavy international investment is both intensifying competition and creating opportunities for cooperation. With a view to taking full advantage of those opportunities, this Agenda also seeks to provide a basis for international collaboration. New bilateral alliances are being sought with Canada, the US and Japan. At the same time, the Agenda aims to promote cohesion and enhanced organization among national players, making it easier for the Dutch quantum technology community to speak with a single voice, particularly in Brussels, where key decisions are made regarding the research and innovation programmes of the future.

The Netherlands' interests are best served by seeking the optimal balance between national strength and international cooperation. The realization of our national ambition to create the Quantum Delta NL, a world-leading centre and hub for quantum technology, represents a sizeable challenge, but a challenge we are quite capable of overcoming from our excellent starting position. That will, however, require the Netherlands and Europe to match the investments being made by others. And we will achieve our goals only if all parties give this Agenda their backing and support its ambition by committing the necessary resources.



> 'This Agenda sets out what needs to be done to develop a quantum delta in the Netherlands: the QΔNL.'

05

FUTURE AGENDA FOR THE QUANTUM DELTA NL

5.1 Four action lines and three CAT programmes

The Netherlands is capable of becoming a Quantum Delta, with a role and dynamism similar to Silicon Valley during the development of transistor technology. However, that will not happen spontaneously: a targeted strategy and approach will be required, to which all parties within the ecosystem give their concerted backing. This Agenda describes the action needed for further development of the technology and applications within the Dutch Quantum Delta – a lively, innovative hotbed of talent, knowledge and resources with strong national and international ties.

The future agenda for the Quantum Delta NL has two dimensions:

Targeted action aimed at reinforcing the entire knowledge and innovation ecosystem. The action needs to address four key drivers of development:

Action line 1
Realization of research and innovation breakthroughs

Action line 2
Ecosystem development, market creation and infrastructure

Action line 3
Human capital: education, knowledge and skills

Action line 4
Starting social dialogue about quantum technology

Three catalyst programmes designed to expedite the market-readiness and social acceptance of promising application areas. The ambitious programmes will serve to pilot and substantiate the technology and enable potential end users to experiment with use cases. The programmes have a cohesive function, bringing together the various technologies and action lines, various ecosystem actors, and the scientific and user communities. The three CAT programmes are:

CAT 1
Quantum Computing and Simulation

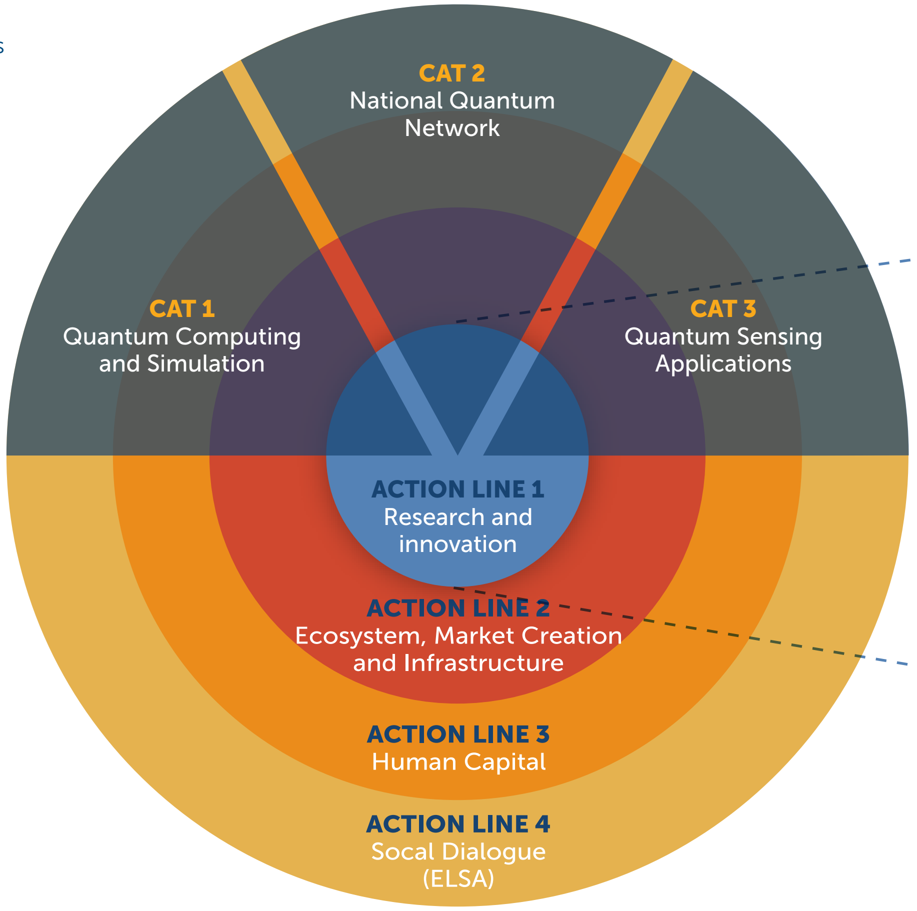
CAT 2
National Quantum Network

CAT 3
Quantum Sensing Applications

A national help desk will be set up to ensure that interested parties have straightforward access to the action lines, CAT programmes and Agenda partners. The help desk will also act as a central point of contact, referring questions to the appropriate players in the ecosystem. Behind the help desk will be a network encompassing all the knowledge institutions and enterprises working on the development of systems, use cases and algorithms throughout the stack, from hardware to software and applications. One of the help desk's functions will be to facilitate use case dialogue between the end users and developers of quantum hardware and software, e.g. by means of use case development workshops, working visits, information sessions, access to test facilities, and so on.

The interrelationships are illustrated Figure 14.

FIGURE 14
Four action lines and three ambitious unifying CAT programmes.



The first action line is divided into the various technologies covered by this Agenda: quantum computing, quantum simulation, quantum communication, quantum sensing, quantum algorithms and post-quantum cryptography. Each of those fields requires its own research and development, as described in subsection 5.2. Action lines 2, 3 and 4 are generic and not technology-dependent; details are given in subsections 5.3 to 5.5.

The CAT programmes are described in subsection 5.6. All are ambitious programmes, intended to accelerate development, to pilot quantum technology in the form of substantive applications, and to valorize and industrialize quantum technology.

5.2
Action line 1 | Realization of research and innovation breakthroughs

The development of quantum technology is supported by a solid basis of innovative research. The envisaged applications of QT will require early-phase research and development, where existing ideas and perspectives are refined and taken forward, and where the scientific and technological breakthroughs and capabilities necessary in that context are realized. For example, to make quantum computing and quantum communication possible on a large scale, it is necessary to improve the specifications of qubit systems, quantum simulators and quantum networks and to scale up such systems significantly. Furthermore, important questions remain to be answered regarding development of the algorithms and protocols needed to fully utilize the potential of quantum information. Within action line 1, the various development pathways are grouped together in six research and innovation programmes: quantum computing, quantum simulation, quantum algorithms, quantum sensing, quantum communication and post-quantum cryptography. The make-up of action line 1 is illustrated in Figure 15.

If the Netherlands is to continue playing a leading role in the future, close cooperation and investment in research and innovation will be required. The objective being to ensure the continued realization of vital scientific and technological advances. The Dutch Research Council (NWO) has an important role to play in relation to early-phase research. Attention will need to be given to the establishment of fundamental and multidisciplinary research programmes in partnership with the business community, to alignment with the National Science Agenda (NWA) and European research

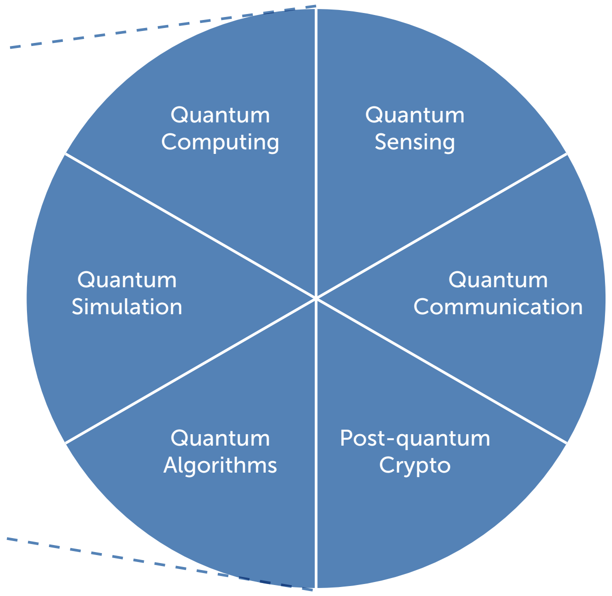


FIGURE 15
Action line 1 consists of six research and innovation programmes.

programmes (e.g. ERA-Net QuantERA, the Quantum Flagship and various ICT programmes), to selection aimed at focus retention, and to the prevention of (unnecessary) overlap between different projects and programmes. Furthermore, NWO and TNO programmes must allow scope for (research into) the application of quantum technology. In the context of programming for innovative advances, the keywords are therefore: fundamental research, multi-disciplinary design, industrial partnerships, social adoption and international cooperation.

5.2.1 Quantum computing

Creating a large-scale universal quantum computer represents a huge technological challenge, for which it will be necessary to research various qubit platforms, error correction, quantum computer architecture and quantum electronics.

Qubit platforms: Realization of a universal quantum computer within a period of years will require the existing qubit platforms to be transferred from laboratory environments and scaled up to form operational systems that are manageable and capable of reliable operation. That implies addressing a number of key scientific questions. For example:

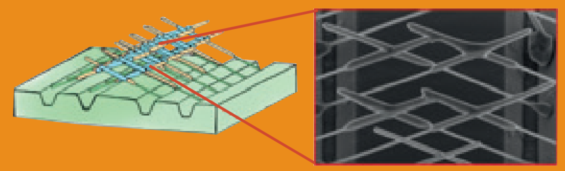
- The ambition is to scale up the current silicon spin qubit systems from two qubits, initially to about ten qubits, and then to a hundred and ultimately a thousand qubits. The challenge is to devise new designs that move away from the classical line geometry, so that scope is created to increase the number of quantum dots per device.
- Where transmon qubits are concerned, the intention is first to implement surface code design on a 49-qubit test platform, and then to scale up towards a hundred and a thousand qubits. The scientific challenges associated with that pathway include managing crosstalk and realizing the 'interconnects' (connections between qubits).
- With NV centres in diamond, the challenge is to create modular quantum computers consisting of numerous nodes, each with about ten qubits. In that context, one hurdle that remains to be overcome is identifying an effective way of connecting the nodes via optical channels.

Error correction: By making a large number of physical qubits function in unison as logical qubits, a universal quantum computer could be used to perform very large calculations, even if the qubits sometimes make mistakes. However, that implies reducing the error rate of the existing systems by a factor of ten to a hundred. It also requires the number of (physical) qubits to be increased by at least a hundred thousand in order to create enough logical qubits to retain the quantum information for a sufficient length of time. One of the biggest challenges in that context is 'connectivity', realizing connections between qubits.

Architecture and electronics: Another challenge associated with building universal quantum computers is the system design and integration of all the hardware and control software. Like the classical computer, the quantum computer

Nanohashtags for braiding Majorana particles

For her doctoral thesis, a TU/e postgraduate student working in Eindhoven and Delft developed a tiny structure of crossed nanofibres in the shape of 'hashtags'.



The structure was created in order to pair and braid Majorana particles. Observation of this braiding phenomenon would provide conclusive evidence for the existence of Majorana particles and would represent a crucial step in the development of Majorana-based quantum computers.[48]

comprises various layers, in which abstract algorithms and quantum algorithms are translated step-by-step into qubit control signals. The technology is currently at the conceptual stage, but as progress is made towards increasing the qubit count, many aspects are likely to be mutually influential: where chip design is concerned, material choices and process steps will influence the coherence time and accuracy of the qubits. The thermal load of the control signals to the quantum chips is linked to the available cooling capacity. The complexity of the electronics and control software is linked to the quality of the chips, and the analysis of measuring signals for error correction requires powerful computers and sophisticated algorithms with a high data-processing capacity and very rapid feedback.

The design and realization of such a complex product requires a form of systems engineering control where trade-offs and system choices are made on an integrated basis, rather than component by component. This Agenda addresses the various issues identified above through the first catalyst programme: Quantum Computing and Simulation. CAT 1 will take the fundamental findings yielded by this action line and use them to develop a mature quantum computer.

5.2.2 Quantum simulation

Quantum simulations will have a major impact on quantum chemistry, materials research and the resolution of fundamental questions in physics. Of course, such simulations are not performed on classical computers, but on specialized quantum devices, called quantum simulators. Quantum simulators utilize quantum mechanical interactions between microscopic particles, such as cold atoms, molecules, ions and light particles, in order to bring about superposition and entanglement. The particles are then contained by force fields so that, by manipulating the particles (e.g. with lasers) and controlling the specific interactions between them, it is possible to simulate other quantum and non-quantum materials. At present, the huge computational power requirement and therefore the cost of simulating the quantum behaviour of complex molecules and materials means that only very small systems can be modelled. However, it is increasingly common for practical technological applications and systems to be designed on the basis of natural materials, implying the use of large molecular systems. Quantum simulators represent a unique opportunity for modelling and developing such complex materials, because their quantum and scaling characteristics are in line with those of the materials under study.

A quantum simulator could not only shed light on the underlying physics, but also help to explain fundamental quantum systems, such as the early universe, which existed in a strongly correlated quantum regime.

[48] See https://www.nrc.nl/nieuws/2019/05/10/met-nanohekjes-bouw-je-stabiele-qubits-a3959834

In the Netherlands, researchers are working on quantum simulators based on cold Rydberg atoms, dipolar molecules and cold ions (or combinations of those particles) and optical cavity arrays (Eindhoven and Amsterdam), on quantum dots and superconducting circuits (Delft), and on photonic clusters (Leiden). Collectively, the systems under development provide the great diversity necessary for advances in quantum chemistry, new materials development and fundamental physics.

5.2.3 Quantum communication

In the future, a global quantum internet will enable new communication protocols and thus support applications such as secure communication and data storage and secure position verification. It will also open the way for the interconnection of mutually remote quantum computers by means of entanglement. Before a quantum internet can be rolled out on a significant scale, various challenges need to be overcome, such as achieving entanglement over large distances and improving the functionality of quantum networks.

Remote entanglement: As a result of attenuation in optical fibres, qubits comprised of small numbers of photons can cover only short distances before they lose their quantum information. A quantum link spanning more than a hundred kilometres therefore requires special quantum repeaters and quantum memory systems: quantum signals cannot be amplified using classical systems, since any manipulation in transit will fatally compromise quantum information. Considerable development work is being done on both quantum repeaters and quantum memory systems. In the period ahead, challenges remain to be overcome in the fields of materials, efficient interfacing between quantum memory systems and light and wavelength modification at the single-photon level. A future European or even global quantum network is likely to consist of both fibre-optic links and satellite links. Because qubits made up of photons will be subject to different influences with each type of link, interfacing the two link types represents a further challenge that will have to be addressed in due course.

Increasing the functionality of a quantum network: For a quantum internet's first useful applications (e.g. secure identification and communication), a quantum link can function with end points (quantum processors) that each have just a single qubit. However, more complex processing and extra functionality (e.g. anonymous quantum computer control) require quantum processors with multiple qubits and a quantum memory. Greater complexity still - in the form of processors with multiple entangled qubits - will be needed for error correction at the end points of the quantum links. Efficient entanglement of qubits in quantum computing systems and the photons in quantum links will require further research as well. Another significant challenge will be making the qubits in processors more robust during quantum network operations.

Finally, various fundamental issues concerning the software used to control the hardware and regulate internet traffic will need to be resolved. Other significant topics include developing a comprehensive quantum internet stack design featuring both hardware and software, and ensuring interoperability between network layers. Because the quantum internet will work in a fundamentally different way from the present-day internet, a new network stack architecture will be required, which is capable of interacting with the current internet stack while also making full use of the specific benefits of quantum communication. This National Agenda addresses the various issues identified above through the second catalyst programme: the National Quantum Network. CAT 2 will take the scientific findings yielded by this action line and use them to develop a mature quantum internet.

5.2.4 Quantum sensing

Quantum sensors open the way for doing things that are not possible with classical sensors. As explained in subsection 2.2.4, various applications of the technology are already commercially available. However, the products involved are merely the first generation. Enormous scope exists for producing new and better types of quantum sensor and addressing new application domains and markets. Further research is needed in order to realize the full potential of quantum sensors.

One focus of such research should be the development of new sensor technologies. The many topics requiring attention include the use of alternative materials, the formulation and development of new working principles (as with the iqClock project's super-radiating clocks), and the detection of optimized quantum states (enabling a particular variable to be measured while other variables are disregarded). Another important focus area will be the improvement of existing quantum sensors. Much can be gained by, for example, making sensors smaller and faster, improving detection efficiency, integrating hardware and software, developing new quantum sensors control and readout software, and developing new and better atomic clocks.

The quantum sensor research currently in progress is strongly application-oriented. Dutch research teams are working with commercial partners and other users to develop new quantum sensor applications. Examples include atomic interferometers for the detection of gravity waves and for other fundamental physics experiments, networks of atomic clocks for applications in geodesy and for the synchronization of radio telescopes, quantum sensors for measuring the acceleration and rotation of objects (enabling position detection without GPS, for example), improved performance in global navigation satellite systems, and the use of atomic clocks to enable ultraprecise navigation on the basis of mobile phone networks. Another possibility being explored is quantum radar. Other applications that could be improved include medical MRI: the use of quantum sensors to detect extremely weak magnetic fields would enable much better images to be produced. Similarly, the measurement of very weak magnetic fields could be very useful in the semiconductor industry, e.g. for testing microchips during and after manufacture.

5.2.5 Quantum algorithms

Within action line 1, an early-phase research and development programme is to be set up to promote the development of quantum algorithms and applications.

Quantum software is developed in a very different way from classical software, and fundamental research questions remain in relation to new programming techniques and strategies for the design, validation and debugging of quantum software. It is also very important to acquire a clear picture of the problems that can actually be resolved more efficiently using quantum techniques. In that context, the following questions consistently arise:

1. What problems can in principle be tackled more efficiently using quantum technology?
2. How can those problems be resolved using new and existing algorithms and software?
3. How can we ensure that hardware and software developments are mutually supportive?

Those questions are certainly relevant in relation to the development of not only quantum simulators and computers, but also quantum networks. Where quantum networks are concerned, another significant topic is new cryptographic functionalities that are not possible on classical networks, even using classical quantum secure cryptography. Attention will additionally be given to the application and extension of existing technologies, e.g. for optimization, machine learning, quantum systems simulation for new materials, and other familiar technologies and application fields.

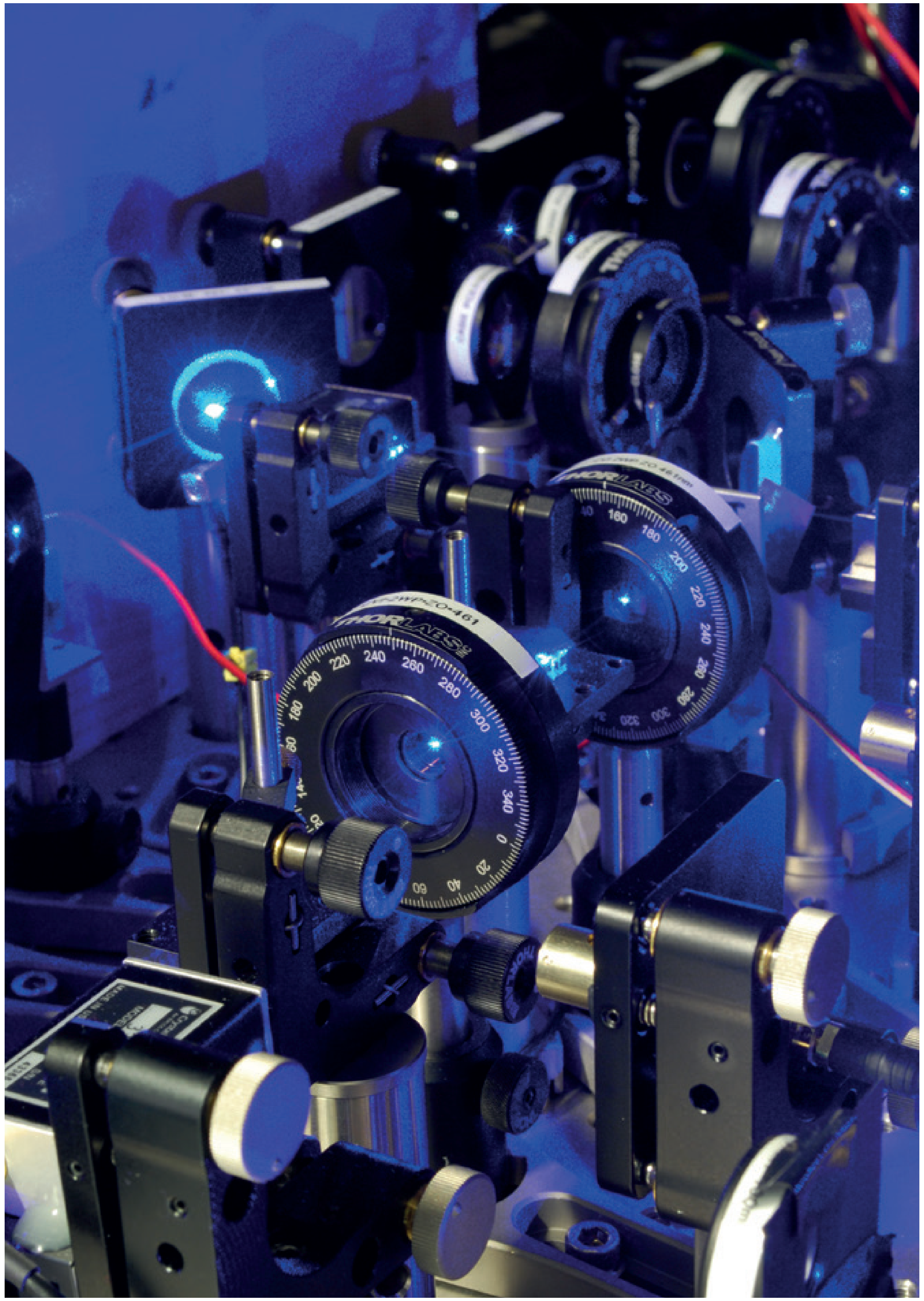
On the basis of those new capabilities, a quantum toolbox will be developed. The toolbox can then be used to explore use cases and thus establish whether the use of quantum technology is advantageous to the end user, when compared with the use of existing, classical applications. Such 'fine-grained analysis' remains in its infancy where, for example, quantum computers are concerned.

In addition to the platform-agnostic developments described above, quantum technology programming techniques will be tailored specifically for the available hardware, including the demonstrators developed in this Agenda's CAT programmes. Questions to be addressed include: 'How many qubits are available and what logical processes (quantum gates) are possible?' and 'How stable are the qubits; is active error correction necessary?'

5.2.6 Post-quantum cryptography

The development of quantum computers has major implications for our digital security. Post-quantum cryptography research and development work therefore focuses on the design and analysis of cryptosystems that are secure in situations where the attacker has a quantum computer, but the targeted user does not.

Various candidate systems are currently under investigation, which are based on mathematical computation problems that cannot be solved efficiently using any available quantum algorithm. However, translating a complex computational problem into a secure cryptosystem requires a great deal of research and development work. In that context, the central questions are:



1. How can a complex computational problem be converted into a cryptosystem so that an attacker can breach the security only by solving the computational problem? What attack and security models apply to the applications used?
2. How difficult is the computational problem, and what are the main parameters that determine its difficulty? Strenuous efforts must be made to find new ways of solving the underlying computational problem, and the complexity of possible attack algorithms must be analysed and understood.
3. How efficiently can the necessary operations be performed in the cryptosystem by the user? What are the main parameters determining the efficiency?
4. How can the necessary cryptographic algorithms be efficiently and securely implemented within software and onto hardware?
5. Exactly how much computational power would be required to successfully circumvent the cryptography using either a classical computer or a quantum computer? The answer to that question determines how large the cryptographic keys need to be in order to assure digital security.
6. What impact will the new cryptographic algorithms have on existing communications infrastructures and business processes, and how can such infrastructures be prepared for the algorithms' rapid and effective implementation?

All those questions will need to be answered in order to develop a secure system. It is important to note that the relevance of cryptography, and therefore also post-quantum cryptography, extends beyond the confidentiality of bilateral communications. Cryptography additionally addresses scenarios where multiple, potentially mutually distrustful, parties wish to jointly realize a functionality. For example, there are cryptographic protocols for purposes such as multi-party computation and distributed bookkeeping.

In relation to the second question, post-quantum cryptography goes beyond pre-quantum cryptography, insofar as quantum algorithms that may run on future quantum computers are included in the analysis. The third question is linked to the second: the free parameters need to be optimized in such a way that the system is difficult for an attacker to breach, yet efficient for the user to employ. Implementation-related considerations (question 4) often lead to redesign in the interests of speed and security.

Points 2 and 5 differ in terms of the level of detail in which the crypto-algorithms are analysed. Point 2 is concerned mainly with the question of how a change to a given parameter influences the security of the system. By contrast, the central issue with point 5 is the number of quantum gates or the amount of quantum memory needed to mount an attack. Account must also be taken of the capabilities of quantum co-processors with low qubit-counts, which will become available well before a fully fledged, universal quantum computer. Other interesting and relevant questions include how the depth of quantum circuits can be reduced and how circuits can be built with gates that require fewer physical qubits.

Post-quantum cryptography research and development must lead to better and more effective systems for securing data and communications. The outcomes will directly influence the digital security of the Netherlands.

5.3
Action line 2 | Ecosystem development, market creation and infrastructure

Quantum technology is at a relatively early stage of development. The expectation is therefore that, in the next five years, growth is mainly going to involve research and development. The Netherlands has several strong centres with the potential to develop into a large, unified national ecosystem. Under the collective banner of the Quantum Delta NL, the scope will be explored for partnering with other actors in the region to invest in joint initiatives capable of reinforcing the Netherlands' position in the field of quantum technology. The CAT programmes will play an important role in that context and will be central to ecosystem development. The following activities will also be set in motion:

1. **International positioning of QΔNL and international embedding of the National**

   – ***International positioning of the Netherlands as Quantum Delta NL***, by organizing and participating in cluster meetings, workshops, conferences and networking days. In September 2019, the Netherlands will have a stand at a quantum conference in Boston; the following month, the first Inside Quantum Technology conference in Europe will take place in The Hague. Consideration is also being given to organizing an international TED quantum event, as well as an annual event for the Dutch quantum community as a whole ('Veldhoven QT Days').

   – ***Embedding within Europe*** | The Netherlands cannot develop quantum technology and the associated market without help. We are therefore actively pursuing collaboration at the European level, where quantum technology is also a high priority. In the context of the European Quantum Flagship, the Netherlands is playing a pioneering role in the fields of the quantum internet and atomic clocks, and Dutch knowledge institutions have responded to a call for proposals relating to quantum software and silicon qubits. The EU is committed to the development of a European Quantum Communication and Quantum Computation Infrastructure. In June, the Netherlands and seven other EU member states signed a joint declaration regarding the European Quantum Communication Infrastructure. The aim is to have an operational European quantum network within ten years, based on a combination of fibre-optic links and satellite links. The network will be used to address public use cases, such as connecting government services and securing critical infrastructures. As the home of ESA/ESTEC, the Netherlands can play an important role in that context.

   – ***Global embedding*** | The Netherlands' commitment to European collaboration does not preclude trans-Atlantic cooperation. The Dutch economy has traditionally been open and knowledge-based, and we have strong partnerships both with international companies such as Microsoft, Bosch, Shell and Intel, and with public research bodies all over the world. In all cases, the central consideration is whether cooperation can sustainably reinforce the technological development and standing of the Netherlands. To that end, it is important to invest in the ecosystems that will encourage parties to put down roots in the Netherlands, as opposed to merely establishing a transient relationship. The campus development in Delft is strategically important in that context.

   – ***Bilateral cooperation with North America and Japan*** | The Dutch Research Council (NWO) aims to establish bilateral programmes for cooperation with the United States, Canada and Japan, where investment by NWO is matched by a corresponding body in the partner country. The programmes are to involve fundamental research across the full spectrum of quantum technology topics. Calls will be made for project proposals involving international consortiums and the exchange of talent, particularly young talent. From 16 to 18 September 2019, a joint Dutch-Japanese scientific conference was held in Delft with the aim of defining the themes for a bilateral call.

2. **Creation of field labs**, i.e. practical environments (as made popular by the Smart Industry Action Agenda) where companies and knowledge institutions can develop, test and implement targeted solutions to the challenges faced by various industries. Focus issues will be derived from the use cases and the collaborative activities taking place in the facilities developed in the CAT programmes. A national plan will be drawn up to ensure advance coordination and alignment. A good example of the type of facility envisaged is the Quantum Lab (subsection 3.2.4) currently under development. That lab will initially concentrate on the water management industry, but will in due course extend its scope to embrace other (possibly national) domains. The creation of field labs and local partnerships of students, researchers, entrepreneurs and secondary schools and colleges can also seed economic activity at this early stage of development. An important feature of the field labs will be their role in bringing together people working with quantum technology - at domain cluster meetings, for example - with the aim of exploring the potential of quantum technology. Ties will also be sought with other key technologies (e.g. artificial intelligence, photonics and ICT) in which the Netherlands excels. To that end, workshops and joint projects will be organized, for example.

3. **Expansion of the national cleanroom facilities required for implementation of the Agenda.** Development of the national ecosystem will depend on investment in the national cleanroom infrastructure. The infrastructure is managed by NanoLabNL and includes centres in Delft, Eindhoven, Groningen, Amsterdam and Enschede.

Investment is required to maintain the infrastructure and to expand it in line with the growth of quantum technology in the Netherlands. In this field, the priority is the NanoLab3 proposal, which provides for investment in, among other things, new equipment for the cleanrooms at TNO, Delft University of Technology, MESA+ and Eindhoven University of Technology.

4. **Further development of the Delft quantum cluster for the Dutch ecosystem**. As home to QuTech, various enterprises, the Quantum Lab and the planned House of Quantum, the Delft quantum cluster (working title 'Q-campus') is the biggest concentration within the national ecosystem. Within the cluster, companies, startups, researchers and students from throughout Quantum Delta NL and all local centres work together on development of the technology, with access to research infrastructure and the national quantum computing facility, part of CAT 1. For the further development of the cluster, it is important to invest in the acquisition and account management team, the accommodation and the shared research facilities, including cleanrooms and workplaces. The Delft cluster will work as an international magnet, and its reputation will be advantageous to the whole QΔNL community, helping to make the Netherlands attractive as a base for high-tech industry. In an intermediate scenario, the Q-campus workforce is expected to grow from its current 300 FTEs to 650 FTEs by 2023.

To support the development of QΔNL, a national **House of Quantum** is to be set up in Delft: a physical, open centre for the quantum technology community that fulfils multiple functions, providing accommodation for researchers, startups and other enterprises, as well as locations for meeting and interaction. The House of Quantum will be an inspiring setting that facilitates random contact between enterprising people at the interfaces between disciplines and domains, a venue for gatherings, receptions, conferences and workshops by

people working with quantum technology. For visitors from other countries, the facility will serve as a base for exploring the wider Dutch quantum ecosystem, since many 'quantum meetings' will take place in other parts of the country. In short, the House of Quantum will be a place where something is always happening and a natural place for meetings. An exact site and a detailed plan for the facility have yet to be decided. Best practice examples elsewhere, such as Toronto's vectorinstitute.ai, will be studied as part of the planning process.[49]

5. **Expansion and reinforcement of local centres within the national landscape.** This Agenda is intended to support and promote cooperation across the various quantum technology initiatives ongoing around the Netherlands. In addition to the developments in Delft outlined above, those initiatives include:

   – ***Creation of a Quantum Application and Software Hub in Amsterdam***. By pooling the brainpower and capabilities of academic institutions in Amsterdam, the support facilities at the Amsterdam Science Park and partners throughout the region, a Hub will be established where the various parties can engage with one another to develop use cases and applications for quantum technology. Within the Hub, collaboration will be organized on the basis of various themes (or field labs), such as Quantum Applications in Finance, Quantum Applications in Chemistry and Materials, and Quantum Applications for Operations Research. The Hub will be open for and promote cooperation among all parties in the Quantum Delta (and beyond), with the explicit aim of expediting innovation in quantum technology software and applications through national and international collaboration.

   – ***Reinforcement of the ecosystem in the Brainport region, around quantum-secure communication links and quantum-secure authentication systems*** in the Brainport Smart District. In the Eindhoven region, cohesion will be sought across the various quantum activities and the internationally prominent high-tech systems and materials cluster.

   – **Development of the Leiden aQa platform** (applied Quantum algorithms, see http://aqa.universityleiden.nl), where theoretical quantum algorithms are adapted to actual hardware, with a view to realizing short and medium-term applications for end users. The platform will build on successful industrial partnerships with Shell (quantum chemistry) and Volkswagen (quantum optimization).

   – ***Reinforcement and interlinking of quantum technology research at the University of Twente's Quantum Centre***. There are activity concentrations at the MESA+ Institute for Nanotechnology, where work is being done in the fields of superconducting devices, silicon quantum electronics and photonic quantum information processing. The link between quantum technology and integrated photonics will be strengthened with the aim of promoting enterprise on Twente Knowledge Park. The initiative will build on successful cooperation between the University of Twente and high-tech SMEs in the region.

6. **Establishment of a technology transfer programme and encouragement of startups**. New business startups are vital to the development of an ecosystem, for two reasons. First, they are important for the growth of a Dutch quantum industry. Second, they aid the retention of talent: they create employment for newly qualified PhDs and others, so that highly skilled people remain within the ecosystem, instead of leaving to pursue career opportunities abroad. A programme will therefore be established to encourage and support scientists and entrepreneurs who want to start new businesses and thus bring new knowledge and technology to market. Taking inspiration from Silicon Valley, the programme has high ambitions. The goals are nevertheless realistic, because the first parts of the jigsaw are already in place: high-level expertise, various startups supplying specialist parts for quantum computers, quantum networks and quantum sensors, and large corporations willing to invest in the Netherlands. The programme provides for the development of a good quantum technology startup policy, with the associated IP frameworks, risk capital facilities, on-campus business accommodation and access to infrastructure such as laboratories and cleanrooms.

[49] *See: www.vectorinstitute.ai*

5.4
Action line 3 | Human capital: education, knowledge and skills

In the years ahead, talent is expected to be one of the factors limiting the further growth of quantum technology and related industries. Because quantum technology is relatively new and based on counterintuitive knowledge, current educational programmes cannot meet the growing demand for quantum engineers and system engineers. There are not yet any academic or technical programmes relating specifically to quantum engineering. Investment in appropriate education and training is therefore required before quantum technology can be properly embedded in industry or society. The QuTech Academy in Delft, the Quantum Information Module and QuSoft Master's in Amsterdam, and the Quantum Materials & Technologies Certificate being developed at QT/e in Eindhoven can serve as foundation stones.

7. **Strengthening education, cooperation and knowledge exchange**, in which context various activities are under consideration, including promoting domestic and international student and programme exchanges and setting up a joint curriculum for quantum programmes at various universities and institutes. Outreach could be increased by sharing (electronic) teaching material and making other material available online. Industrial internships for students are also important, as are courses for people already working in industry: 'teach quantum to engineers, and engineering to scientists'. Commercial partners can be closely involved in such initiatives, through guest lectures on entrepreneurship, software and hardware, for example; the willingness to be involved already exists.

   In addition, quantum technology (or at least its basic principles) can be made more accessible and appealing by organizing eye-catching events, such as international hackathons and challenges. Another idea is to create programmes with and for teachers, with a view to integrating quantum technology into the material taught at secondary schools (and possibly even primary schools), so that the Netherlands is ready for a future shaped by quantum technology. The House of Quantum can serve as an inspiring and open venue for the exchange of knowledge among academics and between academics and industrial product developers. To that end, collaboration will be sought with the QuTech Academy and the Quantum Software Consortium's Talent and Outreach Committee.

8. **Attraction and retention of talent from other countries**. The best people want to work at the world's best institutes. Leading institutes and research teams in the Netherlands can therefore act as magnets for talent from abroad, as well as for Dutch researchers who have taken up postdoc positions in other countries, but would like to return. That can happen only if a strong ecosystem is in place, and a strong ecosystem will in turn attract new talent and generate economic activity. Potentially useful strategies for attracting international talent include creating professorships and posts for quantum engineers and entrepreneurs, and making bursaries available to excellent undergraduate and doctoral students.

9. **Community building, conferences and workshops, summer schools and student exchanges**. In the context of this Agenda, the Dutch Research Council (NWO) has reserved funds for activities that promote cohesion within the quantum community and organization within the field. Building bridges with other academic disciplines, including the humanities and social sciences, is the priority. Appropriate activities include organizing conferences and workshops, and running summer schools and exchange programmes for junior researchers and students.

5.5
Action line 4 | Starting social dialogue about quantum technology

Quantum technology is relatively new. Research teams are vying to make new discoveries, obtain patents and win academic honours. Some governments are already engaging in strategic debate, with vision documents (e.g. the European Quantum Manifesto and Quantum Software Manifesto) and funding programmes. Industry is also starting to recognize the potential and future economic impact of quantum technology. That of course includes major tech corporations racing to build the first quantum computer, but also tech using companies such as banks and aircraft manufacturers. The pace of technological development is high and, with large sums being invested around the world, momentum looks set to build further. However, the full benefit of quantum technology can be reaped only with adequate social support. Because quantum technology currently has relatively few practical applications, the social, ethical and legal parameters largely have yet to be developed. That situation needs to be addressed, because the development of such parameters can play an important role in building social support.

Indeed, dialogue with stakeholders can yield more than social acceptance, as demonstrated by the ELSA meetings organized by Delft University of Technology. The values governing access to technology, such as net neutrality for the classical internet, were also identified by stakeholders as socially important. Some stakeholders went further, highlighting quantum technology applications that they would like to have. In other words, ELSA can also lead to (open) innovation and generate valuable input for all the NAQT's CATs and action lines.

The activities envisaged within this action line are as follows:

10. **Initiation of (international) dialogue regarding quantum technology.** The Netherlands is ideally placed to take the international lead and assume a prominent role in the development of regulatory and ethical frameworks for quantum technology. The Quantum Vision team at Delft University of Technology and the Quantum Software Consortium's Legal & Societal Sounding Board can lead the way in this field, while the House of Quantum can serve as a key physical venue for dialogue. The organization of an international discussion regarding ELSA issues would be a useful starting point, and prominent philosophers, scientists and governance experts can help to push quantum technology up the international agenda. Alignment with European Quantum Flagship initiatives should also be sought and maintained.

11. **Formation of a national ELSA Committee and professorship for quantum technology.** The function of a national ELSA Committee would be to initiate and facilitate national dialogue regarding quantum technology and its implications. It could additionally set up a national programme, with a view to informing and involving all sectors of society, starting with primary schoolchildren. Consideration is also being given to the creation of a professorship in the ELSA of quantum technology. Such a professorship could have the effect of extending the scope of the relevant institute and discipline and representing the Netherlands in an emerging academic field.

12. **Development of legal and ethical frameworks for quantum technology**, partly with a view to generating social support. Existing legal frameworks for the encryption and decryption of information and communication will need to be modified in line with developments in quantum technology. It will also be necessary to address the legal and ethical questions surrounding 'quantum big data', since the huge processing capacity of quantum computers may lead to sophisticated, bulk analysis of very large volumes of privacy-sensitive data. Other ethical and legal questions associated with quantum technology will require attention as well. For example, restrictions on the development, production, distribution and exportation of quantum technology, e.g. trade barriers and export restrictions, can have a major impact on the market in quantum technology, giving rise to pertinent new questions. The responsibilities of cloud-based quantum technology service providers, particularly in relation to the fair and ethical behaviour of users, are also liable to require clarification. For the development of appropriate ethical and legal frameworks, an approach based on 'responsible innovation' is proposed. A national strategy along the lines described can promote and expedite the social acceptance and adoption of quantum technology.

5.6
Three CAT programmes

The three sector-wide CAT programmes are intended to accelerate the process of introducing quantum technology to the market and to society. They will involve the creation of open test environments and facilities where universities, institutes, companies and end users can work together at the national level and experiment with the technology and its applications. System integration, demonstrators, use cases, outreach and multidisciplinary collaboration are the keywords. The facilities developed in the context of the CAT programmes will provide existing and new companies with easy access to quantum networks, quantum computers and quantum simulators. That will lower the threshold to the development and testing of quantum technology and components by removing the need to invest in expensive infrastructure. A large community of developers and potential users can therefore emerge and act as a seedbed for the development of a lively and innovative quantum industry.

5.6.1 CAT 1 | Quantum Computing and Simulation

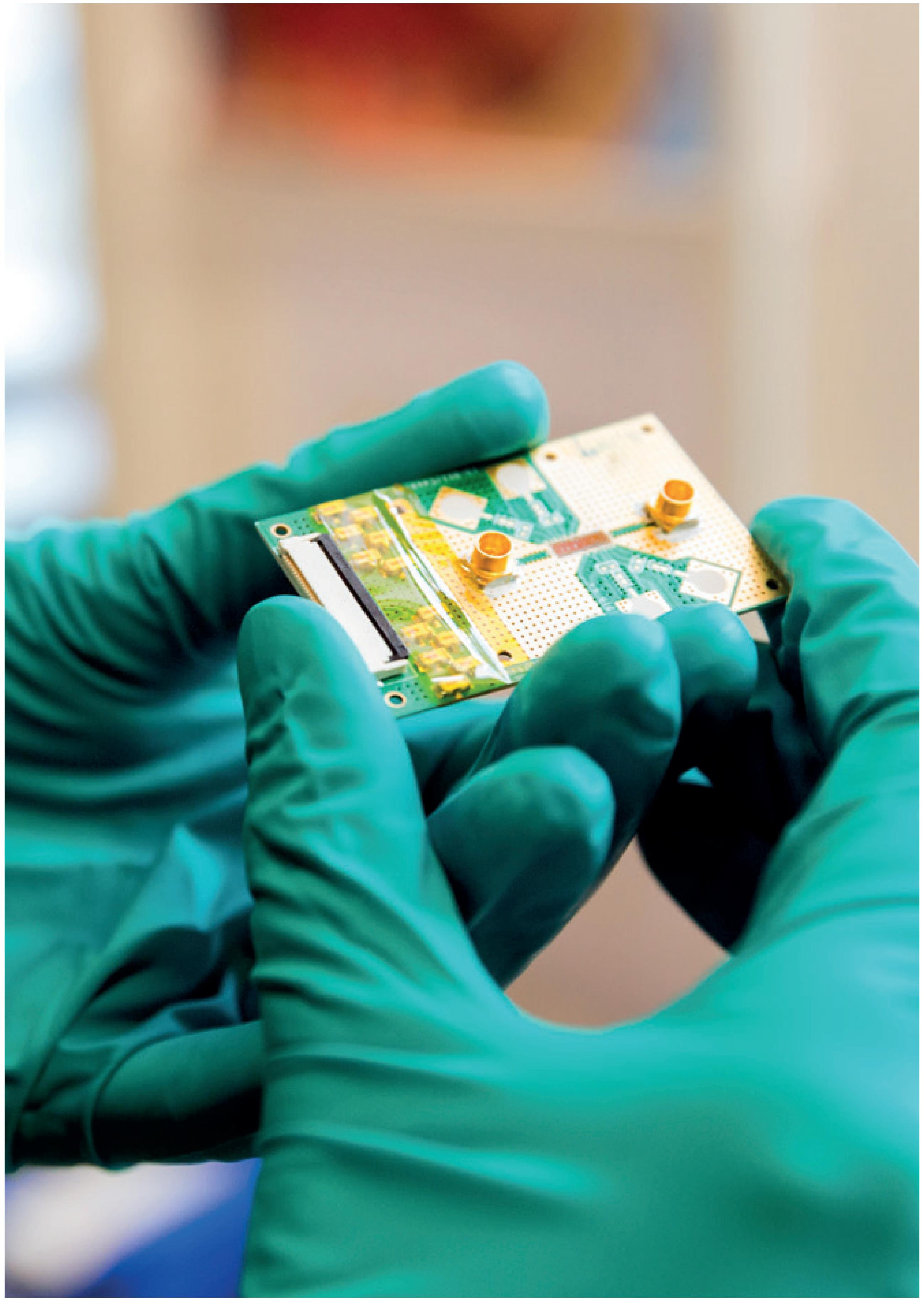
The aim of the first catalyst programme is to expedite the development of quantum computer and simulator technology and its introduction to the market and society, as well as to promote the exploration and further development of such technology's applications. An environment will be created where all the Netherlands' capabilities in this field are accessible, and where government organizations, the business community, technology developers and students are able to explore the full range of possibilities afforded by quantum computing. It will also be possible to gain hands-on experience with implementations on actual hardware and the associated user interfaces, and on the basis of hardware-agnostic implementations. One important focus will be the development of user facilities and demonstrators of appropriate quality (where quality is a function of the number of qubits, the quality of the qubits and the control systems), which can then be made available for the realization of innovative social and industrial applications, leading to the resolution of major social and economic challenges. The development pathway leading to a universal quantum computer will have a number of important intermediate stages, including small ('few-qubit') systems and noisy intermediate scale quantum (NISQ) systems, perhaps based on quantum simulators.

The planned national help desk can put parties within the triple helix in contact with each other and thus initiate dialogue regarding practical use cases and the interaction necessary for the development of hardware and software solutions. That can lead to the formation of broad-based, national collaborations in various application areas, including quantum chemistry and materials development, applications in the financial sector and process optimization in manufacturing and logistics. The emphasis will initially be on use cases where quantum technology has a demonstrable advantage over classical computational solutions.

With a view to expediting technological development, the programme will include the following elements:

1. **Expansion and opening of the physical computing facility in Delft**, including Quantum Inspire and the development of an online platform that gives users and developers access to state-of-the-art quantum computers and quantum simulators in the cloud. Via the online platform, researchers will be able to access various facilities in the Netherlands and elsewhere in the EU for the development of algorithms, software and practical use cases. The facility can therefore become the first European quantum computer, which can be accessed by users - including the general public - making the technology visible and tangible. This European quantum computer will make it possible to get programming experience on a variety of prototype few-qubit quantum computers. For the next few years, the machines in question will be NISQ systems without error correction, such as the hybrid quantum-classical simulators developed in the context of this CAT. The parallel development of the computing capability in Delft and the simulator capabilities throughout Quantum Delta NL may be expected to reduce the time needed to progress from NISQ systems to a universal quantum computer. To support the development of actual quantum platforms, quantum emulators will be developed and made available. Quantum emulators are classical computer systems capable of emulating quantum systems with up to a few tens of qubits. Such emulators have an important role to play in the early development of algorithms and protocols for subsequent implementation on actual quantum systems.

2. **The programme will provide for the development of quantum simulator capabilities** for the development of new materials for a wide range of applications, as well as for an R&D network to which the various simulator platforms in Quantum Delta NL are connected. The network of platforms in Eindhoven, Twente, Delft, Amsterdam and Leiden will open up expertise in the field of quantum simulators and make it accessible to end users, partly through the planned online user interface. The simulator platforms will offer a wide range of systems based on cold atoms, ions and molecules, as well as optical cavity arrays, quantum dots and super-conducting circuits and photonic clusters. In Eindhoven, a demonstration quantum-classical simulator is being developed, with up to a hundred noisy qubits based on Rydberg atoms. The machine will be made available to end users with a view to enabling the resolution of complex materials science problems.



3. **Within this CAT, use cases will be developed** at various locations and in various ways, and made available to end users by the national help desk. For example:
   a) As part of this CAT, the Quantum Application and Software Hub Amsterdam will contribute to the development of applications and software for use on NISQ systems, e.g. for resolving process optimization and materials development problems.
   b) The Leiden aQa platform will work with end users to develop use case-specific benchmarks for quantum algorithms, and will investigate the scalability issues with simulators and on hardware. The work will provide end users with information about the 'rendezvous moment' when the quantum computer will overtake the classical computer.
   c) Field labs will play an important role in translating growing quantum computing and simulator capabilities into concrete solutions in relevant application areas. At the South Holland field lab, for example, researchers are investigating how quantum computing can be successfully used to address water management issues.
   d) By making intelligent use of quantum emulators, the business community can get an early indication of the potential and limitations of quantum computing applications. That will hasten the identification of viable use cases in various sectors and guide the development of appropriate capabilities.

4. **Building up the value chain.** The development, maintenance and operation of the facilities will necessitate input from a variety of players within the scientific lab community and beyond, including control electronics suppliers, software developers, device manufacturers and operators, client contact personnel and app developers. Some of those roles have no existing players, implying that startups and other new players will need to enter the chain. As they do so, the ecosystem will gradually evolve into a value chain for quantum computing. The laboratory infrastructure will need to be upgraded by investing in qubit platforms, a rig for testing functionalities before they go live, and support facilities such as cleanrooms and workplaces. Algorithm and application toolkits will be required as well, along with a quantum software module standards library and test facilities for emulation on supercomputers.

Short-term impact (0-4 years):
This CAT programme's short-term impact will stem mainly from the development of the first European quantum computer and a new, multidisciplinary community around that computer. The use cases developed will lead to the formation of new partnerships, some between parties in sectors that normally have little contact with each other. That will generate new insights and ideas for hardware and software commercialization. The development of a viable platform will depend on the involvement of various existing suppliers of products such as vacuum systems, cooling systems, laser systems and magnet systems.

Medium-term impact (5-8 years):
In the medium term, a new quantum industry is expected to spring up to develop and manage the facilities needed by the quantum sector. The social impact will derive from the new chemical processes, materials and smart production systems whose development will be enabled. It will be felt mainly in industries engaged in biological and chemical processes, such as the production of raw materials for use in construction and agriculture, and the production of fuel, biomaterials and pharmaceuticals.

Long-term impact (8 years and beyond):
The upgrading of facilities will ultimately lead to the development of NISQ technology capable of making increasingly complex calculations, including scalable prototype components for all layers of the stack, such as qubit platforms and control electronics. That in turn will generate applications in various sectors, including the chemicals industry, logistics, ICT (artificial intelligence, machine learning) and health and social care. The Netherlands will position itself as the place where the tone is set for the development of both quantum technology and its applications. Thus, a sound basis will be laid for the ultimate development of a universal quantum computer.

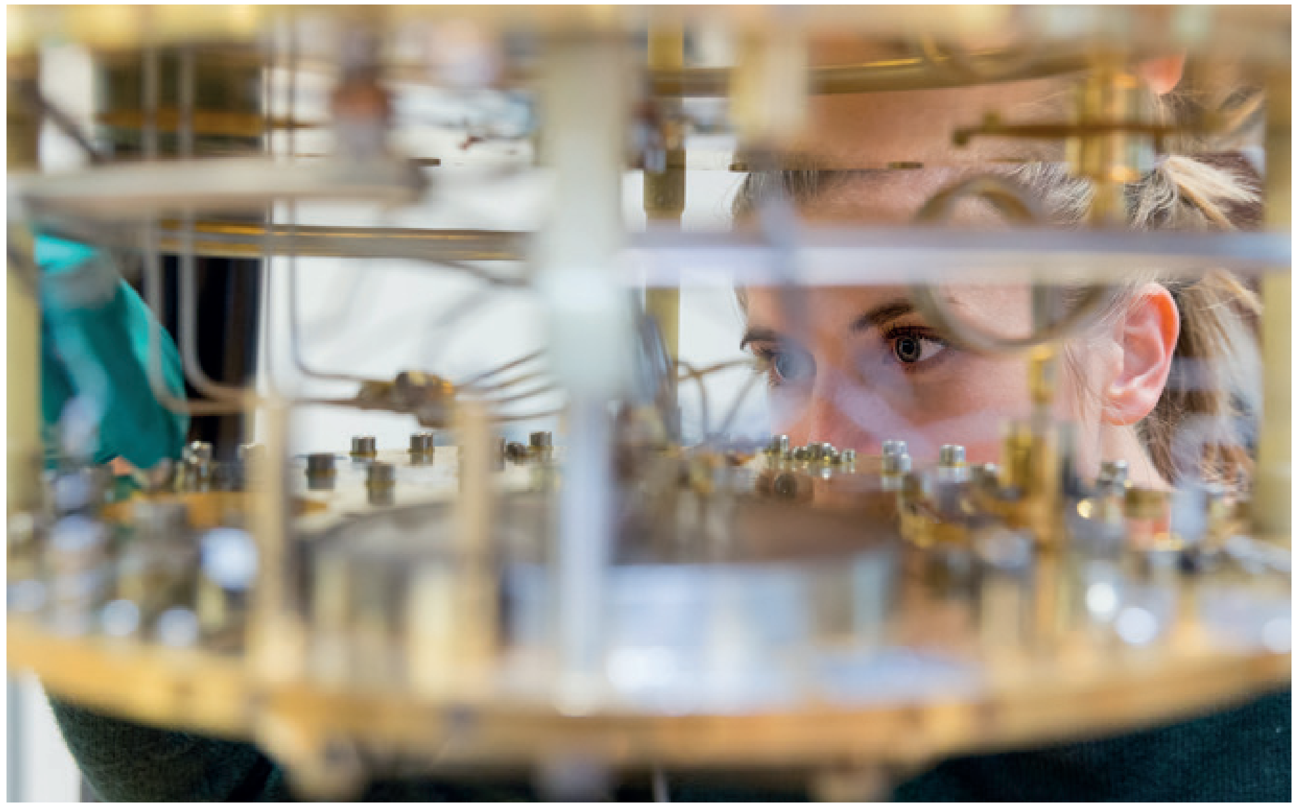
5.6.2 CAT 2 | National Quantum Network

The Netherlands is an international pioneer in the field of quantum communication networks. In the west of the country, QuTech is working with KPN and others to build the world's first quantum internet based on entanglement. Meanwhile, in Eindhoven, the first steps are being taken towards creation of a QKD network in the Brainport region. At the European level, the QuTech-led Quantum Internet Alliance is developing a blueprint for a European quantum internet, and terrestrial and satellite QKD have been identified as core technologies for the Digital Single Market. The National Quantum Network will serve as a testbed for the new technology and for applications within the ecosystem. One of the reasons that the classical internet was able to grow so quickly was that, from the outset, access for network engineers, programmers and users was straightforward and cheap. The creation of similar circumstances can give the quantum internet the boost needed to take it to the next level. One aim of this programme is to lay a basis for national quantum-secure connections, including national access for the testing of relevant innovation questions and industrial applications. In addition, the National Quantum Network provides an ideal starting point for growing a European network. In the latter part of 2019, EU states are drawing up initial plans for a European quantum communication infrastructure (QCI); hence, this is the ideal time to be proactive and adopt a leading role.

Through the national help desk, prospective end users, social institutions and citizens can make contact with various parties working on the national quantum network and with the Quantum Delta NL researchers involved.

The planned National Quantum Network will have three pillars:

1. **A quantum internet infrastructure based on entanglement**, where the first quantum link between Delft and The Hague will be extended to cover the western conurbation and in due course possibly the whole of the Netherlands. The initiative will provide scope for fundamental innovation, further technical development and partnerships with the hardware and software industries for the development of various infrastructure components. It is envisaged as a 'moon shot' that will showcase the high-tech capabilities that quantum communication will bring to the Netherlands. To that end, we have a rock-solid base on which to build: three years after the first ever long-range quantum link was realized in Delft in, the same research team achieved 'entanglement on demand' in 2018. The new entanglement protocol opens the way for three or more quantum processors to be interconnected in the first step towards rollout of the quantum internet.



2. **A development testbed, with open access for users and developers.** An open testbed of this kind will enable the development of a lively and innovative software and security industry based on a future quantum internet. Existing and new software and security companies will have easy access to the quantum network via a user interface, without the need to invest in (currently) expensive quantum hardware and fibre-optic infrastructure. A large community of developers and potential users can therefore emerge. The testbed will initially be based on the emulation of a quantum network using simulation tools recently developed by QuTech, which allow a classical supercomputer to act like a quantum network. Once the technology for this quantum network has been developed to the point where it is ready for user testing, it will be connected to the testbed's user interface via the intermediate software stack.

3. **Connection of early adopters (or bridging the gap in the value chain).** Some facets of quantum network technology are already mature enough for testing by early adopters. The first initiatives in the Netherlands are as follows (see also Figure 16):
   a) The QKD network in the Eindhoven region, where quantum secure point-to-point connections are being realized between a house in Helmond and the TU/e campus so that transmitted data can be secured using quantum keys. Work has also started on a second quantum-secure connection, with Waalre town hall. Another key feature of the initiative, along with the realization of quantum secure connections, is the refinement of quantum-secure authentication concepts to create scalable applications and products.

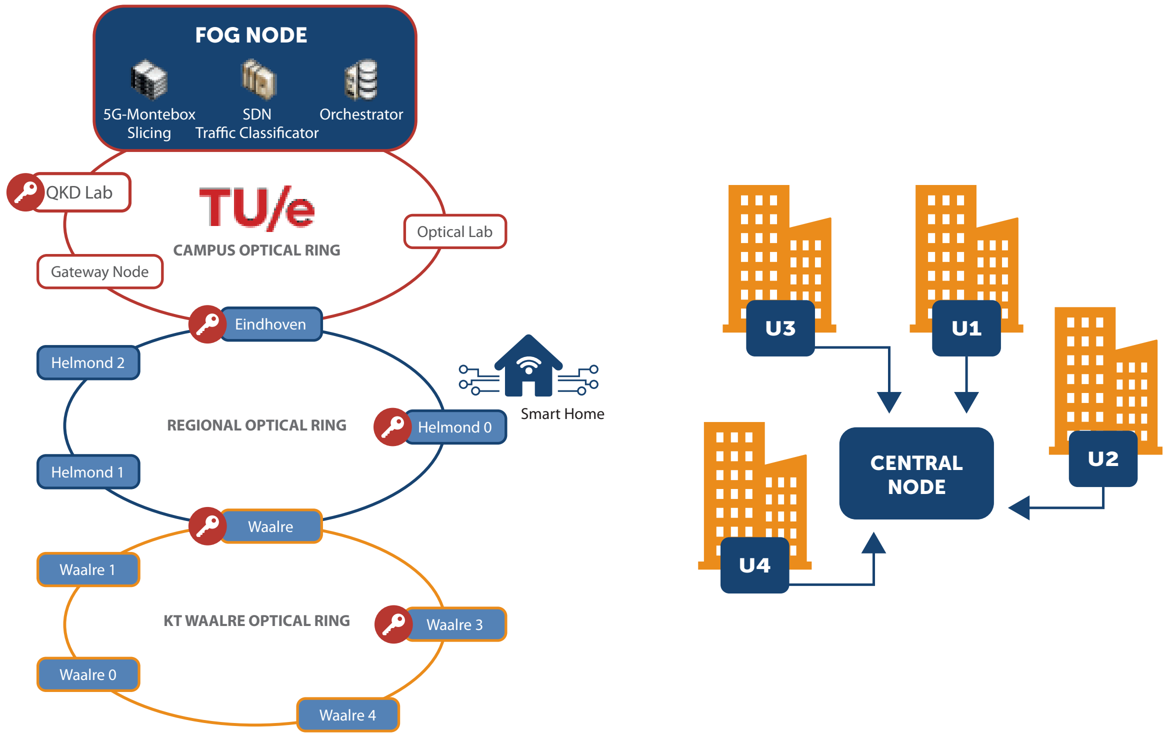


FIGURE 16
The first QKD network testing initiatives in the Netherlands. Left: the QKD network in the Eindhoven region. Right: an MDI-QKD network of the kind planned for the Delft-Hague region.

   b) An MDI-QKD network in the Delft-Hague region, featuring quantum-secure star networks. Using Measurement Device Independent QKD, multiple users can be interconnected via a central node, removing the need for 'trusted repeaters' between the various parts of the quantum network. That results in greater flexibility than is possible with standard QKD systems: the central node acts as a switchboard, constantly connecting users to one another. Another advantage of this MDI-QKD is that, in contrast to standard QKD, it is not necessary to make any assumption regarding the correct performance of light detectors: MDI-QKD cannot be hacked by targeting the detectors. Using the same method, it will ultimately be possible to connect several quantum networks together, thus forming a quantum internet ('internetworking' being the interconnection of multiple networks).

Short-term impact (0-4 years):
A national quantum network to showcase the Dutch quantum industry. Development of the National Quantum Network and associated security systems and applications will demonstrate the potential of quantum technology to the general public. Thus, the National Quantum Network can serve both as a showcase for the Dutch quantum industry as a whole, but also as a platform for education and training of future software and security engineers.

Medium-term impact (5-8 years):
Formation of and connection to a European quantum network. The design of our National Quantum Network can be used as a blueprint for expansion on the European level and as a connection to networks being rolled out in the other countries. First, point-to-point QKD links will be established at the higher level, after which the functionality will be increased by introducing innovations from fundamental research.

Long-term impact (8 years and beyond):
A global quantum network. In the future, the quantum internet will interconnect multiple quantum nodes and quantum computers using both fibre-optic and satellite links. That will create unprecedented opportunities for users, from colossal computational power to a fully secure communication infrastructure. The National Quantum Network will prepare potential users, the general public and the business community for the coming quantum era.

Implementation following the action lines of this Agenda:
Alongside the fundamental quantum network research in action line 1, as described in subsection 5.2, CAT 2 is particularly intended to promote ecosystem development, market creation and infrastructure formation. A National Quantum Network will make it possible both for a quantum communications industry to become established and for service providers like those associated with the existing internet to emerge. Furthermore, the pillars of the National Quantum Network will literally and figuratively connect the various universities and institutes and the participating hardware and software companies and suppliers. The open quantum internet's testbed infrastructure will also afford access to potential users (such as banks, government agencies and security companies) and to developers. New users will be able to experience the capabilities of quantum technology and thus benefit from and become familiar with technologies to which many other companies do not yet have access. That will give companies based in the Netherlands a competitive advantage.

An open quantum internet testbed can serve as a resource for the training of future quantum engineers and users, and as a showcase for the capabilities of quantum technology. For example, the network can be opened to university students and to secondary pupils and college students undertaking relevant projects.

Finally, various aspects of the quantum internet, such as improved privacy, governance, net neutrality and access, are important in relation to the social dialogue regarding quantum technology. Dialogue will also be required regarding standardization and (internet) protocols. The European Telecommunications Standards Institute (ETSI) has set up a QKD Industry Specification Group, while the Internet Engineering Task Force (IETF) is also looking at protocols for a future quantum internet. As the quantum internet grows, it will be important that those and other social aspects receive sufficient attention, and that is what this CAT programme is intended to ensure.

5.6.3 CAT 3 | Quantum Sensing Applications

The classical sensors currently used in, for example, mobile phones, cars, aircraft and spacecraft generally rely on electrical, magnetic, piezoresistive or capacitive effects. Many are based on the mechanical oscillator principle, which allows a variety of parameters to be measured, including pressure, temperature, charge, mass and acceleration.

Although such sensors are very sensitive and efficient, they are fundamentally limited by, for example, classical and external noise. Future sensor applications will require significantly greater sensitivity than can be achieved with existing designs; ideally they should be limited only by the ultimate parameters of quantum mechanics. Furthermore, certain applications require sensors that are insensitive to electromagnetic scatter, which is abundant in and around MRI scanners, electric vehicles and many other machines and appliances. Quantum sensors can potentially meet such emerging requirements.

At the present time, the quantum sensor area is probably the most mature of the four quantum technology application areas in terms of industrial and general application. Nevertheless, a great deal of research remains to be done in this area. As well as research into fundamental aspects (the invention of new quantum sensors and the improvement of existing ones), it will be necessary to identify new uses and to design and develop profitable and sustainable applications. Various organizations and teams in the Netherlands are working on such challenges, often in partnership with sponsors from the business community. However, it is a fragmented landscape, where the step from experimental lab system to viable commercial system is often a long one, and where the Netherlands, despite its excellent research in the field of quantum sensing, has yet to establish an international presence. This CAT programme is therefore intended to promote cohesion and expedite the development of quantum sensors.

A multidisciplinary cooperation platform will be established, where researchers and developers can exchange experiences, share resources and partner with enterprises and end users in various sectors to define use cases and develop corresponding prototypes. The CAT programme will focus explicitly on users in various domains: defence, space travel, manufacturing, mobility, agriculture, and so on. One significant feature of the programme will be facilities where new types of quantum sensor can be demonstrated as a starting point for collaborative further development. Within this CAT programme, fully functional prototypes will be developed on the basis of technologies with which the Netherlands excels, such as systems based on quantum mechanical oscillators, ultracold atoms, NV centres in diamond and transmon qubits.

Applied research, system integration, domain expertise and benchmarking relative to existing sensors will also figure prominently in the programme. All those elements are required in order to determine what is necessary following the concept phase in order to continue development to the point where the product is useful to an end user and economically producible by a (future) sensor manufacturer. The CAT programme's prototype development activities will therefore also be directed towards the identification of the critical support technologies needed to take quantum sensing to the next level (such as photon and atom sources and detectors, quantum mechanical resonators, photonics and electronics). Companies working on such technologies will be involved in the development of the prototypes, with a view to triggering the development of a supply chain for quantum sensing.

The programme has two main strands:

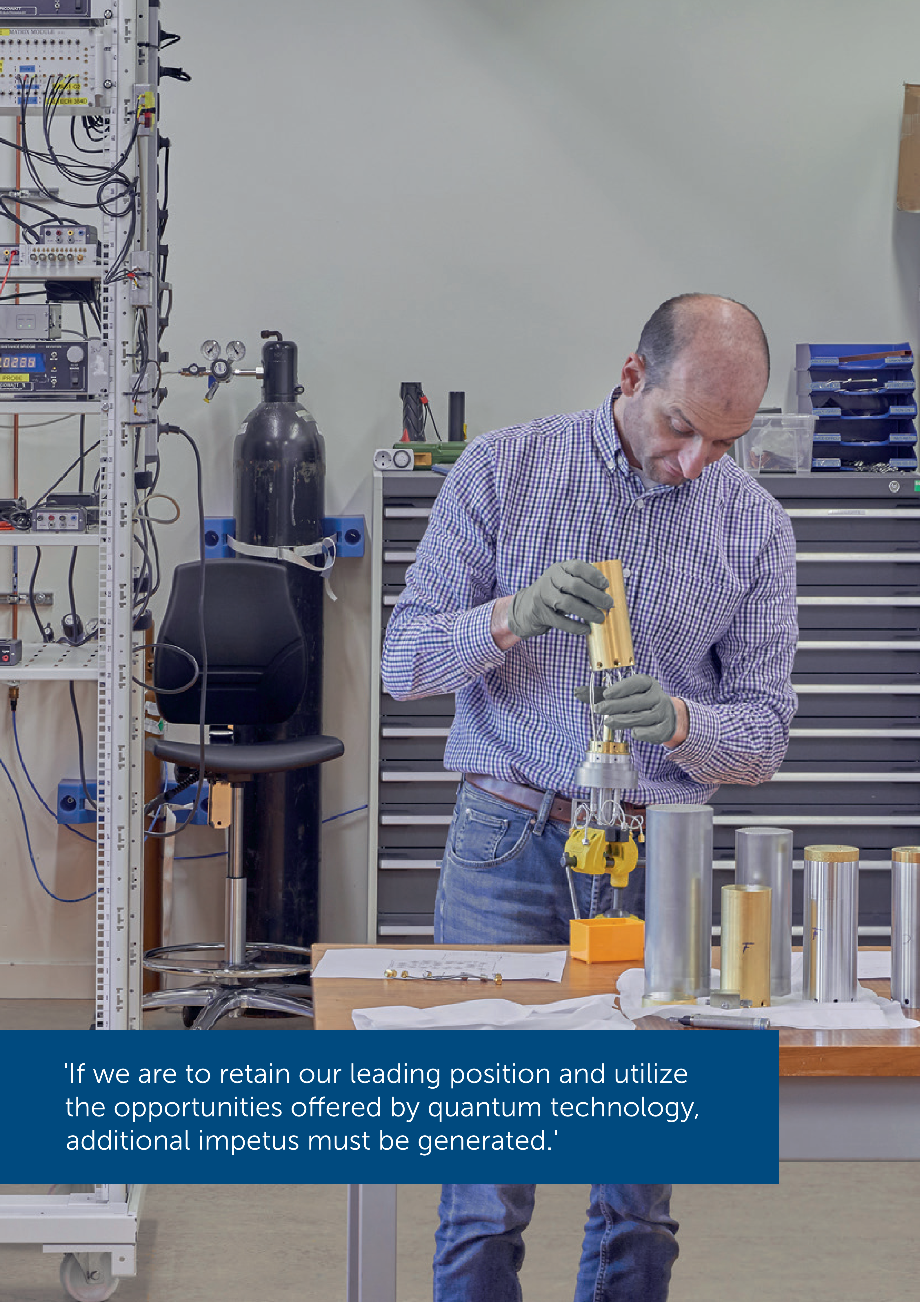
1) **Establishing a platform for joint innovation in the field of quantum sensing**, where scientists, systems engineers, hardware and software companies and end users can work together on the development of new applications for quantum sensors. By organizing workshops, network meetings and innovation fairs, commercial actors can be brought into contact with scientific teams and institutes. Organizations that specialize in applied research, such as TNO, will help to recruit appropriate parties and put them in contact with one another. The platform will help to guide the scientific research that is needed, while the findings of ongoing research will serve as input for the identification of new application areas and use cases. The platform will be a network were parties come into contact and new partnerships are formed. Educational institutes will be involved in the platform as well, so that the workforce of the future is equipped to use quantum (sensor) technology.

2) **Realization of a testing and user facility for quantum sensors**, to assist enterprises and other organizations to prepare technologies for market. The intention is to realize a widely accessible, national user facility. It may be spread across the sites of the various platform participants, who all open up their own facilities. The platform will serve as a help desk for the distributed facility. The involvement of scientists, systems engineers and developers from the business community will result in a lively community, where the capabilities of the testing and user facility are continuously extended in consultation with end users.

Short-term impact (0-4 years):
A new, multidisciplinary quantum sensing community is to be developed within four years. The aim will be to end the current fragmentation of the landscape and to secure a high profile for the Netherlands in the field of quantum sensing, with the purpose of expediting the development and application of quantum sensors in various domains and resolving the associated (technological) challenges. The result should be new partnerships and new ideas, and the development of new products and services. The first steps towards realization of a national quantum sensor testing and user facility will be taken in this period.

Medium-term impact (5-8 years):
In the medium term, new sensor technologies under development will be translated into market applications. Existing solutions will be improved and focused efforts will be made to promote the industrialization of quantum sensor production processes. New Dutch companies will be founded and reach maturity. By this stage, the national testing and user facility will be an established part of the Dutch quantum delta, accessible to parties in the Netherlands and other countries.

Long-term impact (8 years and beyond):
After eight years, the Netherlands will have established itself as one of the world's leading quantum sensor nations. Dutch companies will be active along the entire chain, from concept development to the delivery of sensor solutions to end users, working closely with the academic community.



'If we are to retain our leading position and utilize the opportunities offered by quantum technology, additional impetus must be generated.'

06

CRITERIA FOR IMPLEMENTATION OF THE AGENDA

6.1 Organization and governance

This Agenda is the collaborative product of a core team drawn from the golden triangle and made up of people with diverse backgrounds but a shared goal. It draws on the expertise of a consultation group of more than fifty leading figures in the field. The Agenda is a starting point for a process by which the plans are translated into a practical programme of action. The form taken by that programme will depend on decisions to be made in The Hague regarding realization of the government's key technologies policy. Operating as a coalition, the core team is willing to oversee implementation of the Agenda, and intends to apply itself to that task energetically.

6.2 Funding

The Netherlands's prominent position in the quantum technology world is attributable not only to scientific excellence, but also to the political and managerial courage of previous governments and parties such as FOM, the Dutch Research Council (NWO), TNO and the universities in Delft, Amsterdam and Eindhoven. In recent years, considerable amounts of public and private capital have been invested in QuTech, QuSoft, Eindhoven University of Technology and the Gravity programme. As a result, the Netherlands occupies a strong position in European programmes such as the Quantum Flagship, launched during our country's presidency of the EU. However, as Robbert Dijkgraaf said at the presentation of the excellent QuTech midterm review: the Netherlands has something globally unique, which is both a privilege and a responsibility. If we are to retain our leading position and utilize the opportunities that quantum technology offers for science, the economy and society, additional impetus must be given to the defined action lines.

The total annual cost of the programme, including programmes already in progress, is estimated to be 102 million euros per year, of which 69 million is covered by current programmes. The new action lines will require the investment of 34 million per year. In relation to the potential and impact of the Agenda, that is a very modest sum. The table below provides an indicative summary of the resources required for the various CATs and action lines. The figures are based on the Key Technologies Multi-year Programme submitted by the Quantum NL coalition in connection with the KIA/KIC.

CAT / Action line	Total € million/year
CAT 1: Quantum Computing and Simulation	7.0
CAT 2: National Quantum Network	4.5
CAT 3: Sensing Applications	2.0
Action line 1: Realization of research and innovation breakthroughs	8.0
Action line 2: Ecosystem development, market creation and infrastructure	9.0
Action line 3: Human capital	2.5
Action line 4: Social dialogue	1.5
Total	**34.5**

Colophon

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