97

The Technology Monitor 2020

Quantum Technology

Roland Ortt
Delft University of Technology

Commissioned by
The Netherlands Study Centre for Technology Trends
(Stichting Toekomstbeeld der Techniek)

Stichting Toekomstbeeld der Techniek

Stichting
Toekomstbeeld
der Techniek

Colophon

Research and projectmanagement: *dr. Roland Ortt (TU Delft)*
Text and language editing: *dr. Patrick van der Duin (STT), Franca Gribnau (STT)*
Design & DTP: *IM VormCommunicatie, Den Haag*

NUR-nr. 950

Keywords:
Technology, Quantum Technology, Innovation, Netherlands

This report is an abridged and edited version of a report in Dutch with the title “De Technologiemonitor 2020 Quantumtechnologie”. The Dutch report can be found via the website stt.nl.

ISBN: 978-94-91397-25-7

Stichting Toekomstbeeld der Techniek
Koninginnegracht 19, 2514 AB, Den Haag
070-302 98 30
info@stt.nl
stt.nl

Table of contents

	page
Foreword	04
Introduction	06

Chapters

1	Quantum technologies and their applications	09
2	Patterns and factors of the development and diffusion of Quantum technologies	19
	Introduction	20
	The atomic clock and other Quantum measuring and sensor technologies	21
	Quantum cryptography and other Quantum communication technologies	28
	The Quantum computer	36
	Conclusion and discussion	40
3	Conclusions	41
	Introduction	42
	Answers to the research questions	43
	Practical recommendations	47

Sources: references and consulted websites	51
Appendices	54

Foreword

It has been argued that we are now living in the Anthropocene. Both the world around us, as well as our own lives, are increasingly determined by human actions. Everyone can decide for themselves whether or not that is a good development. It may be comforting to think that, if the world is not in 'good shape' now, that it is our own fault, and we may be able to do something about it ourselves.

Dr. Patrick van der Duin, managing director of The Netherlands Study Centre for Technology Trends (STT)

March 2021

But I am not sure the term 'Anthropocene' covers all of reality, and would like to introduce the term 'Technolocene'. After all, do we not live in a world and a society that are very much inspired and determined by technology? And have rapid and influential technological developments not become the main driving force? In that sense, the question is how the Anthropocene and the Technolocene are related to, can complement and perhaps stimulate each other. And aren't Technolocene and Anthropocene false opposites? It is no coincidence that technology philosopher Peter-Paul Verbeek (University of Twente) argues that we cannot view mankind and technology separately from each other.

An intriguing example of the Technolocene is the development and diffusion of quantum technology, the subject of this study. Quantum technology is not one technology, but a collection of technologies, or a 'discipline', as the author Roland Ortt puts it. As such, the state of affairs in quantum technology is not a single one. Some areas of quantum technology are already well developed, while other parts are not, and some applications of quantum technology are already on the market, while others are not (not yet anyway).

The decision to map the development and diffusion of quantum technology was not a very difficult one. Expectations are high. Quantum technology is a so-called General Purpose Technology (such as electricity or the Internet), a technology that affects every sector or domain. Quantum technology will also have a major social impact, for instance by making it possible to communicate without being hacked.

“Imagine a particle that can be in two places at the same time....”

The decision was also made easier, because STT’s Technology Monitor 2018 (on blockchain, autonomous vehicles, 3D printing and augmented reality) was a great success. In part because of the COVID-19 crisis, it turned out that analysing an entire discipline was more difficult and time-consuming than expected, but the result is impressive. Quantum technology is not an easy subject. The underlying scientific principles are difficult to reconcile either with existing scientific insights or with our human intuition. Imagine a particle that can be in two places at the same time.... But that is precisely why quantum technology is so fascinating, and it is quite possible that its social and economic potential runs parallel to that.

Introduction

Research questions

This reports looks at how far Quantum technologies are in their development and diffusion, what the exact course of that development and diffusion is and which factors hamper or stimulate their progress. To answer those questions, underlying principles of the Quantum technologies, their function and their applications are discussed.

This report focuses on the following research questions:

- **What are Quantum technologies?**
- **What is the pattern of development and diffusion of the Quantum technologies and what is their current position in that pattern?**
- **What are the factors that hamper or stimulate further future development or distribution?**

Importance of Quantum technologies, the predictions and the debate

Batteries that last 10 years per charge. MRI scanners the size of smartphones. Medical sensors that diagnose disease with nothing more than a breath sample. At Moscow's fourth annual International Conference on Quantum Technologies, the world's quantum physics community acknowledges this fantastic-sounding stuff as completely realistic. *https://www.businessinsider.com/quantum-technology-2017-7?international=true&r=US&IR=T*

Technological breakthroughs, like Quantum technologies, affect different elements of society and in the long term also the daily lives of citizens, and almost all public and private organisations. In the past, the impact of steam engines was not limited to mining, for instance, the industry where they were first applied. After Thomas Edison improved the steam engine, over time it proved to be a deciding factor in the organisation of many factories and, ultimately, the organisation of society as a whole. Quantum technology can have a similar indirect effect on elements of society. The significance of Quantum technology is expressed, for instance, in various predictions, three of which are mentioned in the margin.

Predictions can be very important for the development of a technological discipline. The predictions can indicate objectives and be part of a vision that can provide different parties with direction and convince those parties to work together. Predictions create expectations that can set parties in motion. That is important, because the application of Quantum technologies requires a broad range of market parties and governments to coordinate their activities. In addition, predictions can also play a role in informing the general population about a new discipline, in the way U.S.-President John F. Kennedy's famous prediction in 1961 "we are putting a man on the moon" did.[1]

[1] The speech in which this prediction was made, was given by the American President John F. Kennedy in the Rice Stadium in Houston, Texas, on September 12, 1962.

Recent efforts are being made to engineer quantum sensing devices, so that they are cheaper, easier to use, more portable, lighter and consume less power. It is believed that if these efforts are successful, it will lead to multiple commercial markets, such as for the monitoring of oil and gas deposits, or in construction. ***https://en.wikipedia.org/wiki/Quantum_technology***

Quantum computers will not replace traditional computers, but may facilitate certain calculations for which traditional computers will probably never be powerful enough. That can lead to revolutionary applications, like solving complex optimisation issues or predicting, simulating and modelling the behaviour of molecules, catalysts or new materials. ***(National agenda Quantum technology, 2019, p. 21)***

That prediction was the start of a collaboration between many organisations, ultimately to enable the first moon landing. The problem with new technology is that it is hard to predict in the early stages of development what the potential applications and products are, which means that visions can often be limited and misleading. The aim of Quantum technology is less simple than putting a man on the moon.

At the moment, most information and predictions about Quantum technology come from scientists and well-informed experts and policy-makers. At this stage, the predictions are mostly about the (technical) possibilities of Quantum technology, about the time frame within which those possibilities will become available and about the potential benefits of applications of Quantum technology in our society. That paints a rather rosy picture.

It is probably due to the complexity of Quantum technology that there will also be nonsensical predictions. That is as old as the phenomenon of technological innovation. Microwave ovens were said to make food radioactive and cause cancer, while some claim that 5G radiation causes corona. All utter nonsense. Quantum technology will generate its own nonsensical predictions and they will spread quickly. The various predictions will probably lead to a debate between groups that do not speak each other's language.

When the first applications of Quantum technology will lead to problems, negative predictions will become louder. Rarely has a technology been developed without things going wrong or accidents happening. Throughout the history of science, there are plenty of examples of that. And if then problems, unintended side-effects and accidents happen, it often becomes clear that the experts have been too optimistic in their predictions, on the one hand providing fuel to the people who made nonsensical predictions, but in the case of accidents, also giving support to people with expertise who are worried. And the debate will shift.

The development over time of the expectations regarding a new technology is expressed in Gartner's Hype curve (Dedehayir and Steinert, 2016), which indicates that, at first, expectations surrounding a new technology are very high. However, when the development takes longer than expected, or when limitations, problems, negative side-effects and accidents occur with its initial applications, those expectations collapse like a house of cards. It then takes a while for expectations to rise again. It appears that expectations move far more quickly than the technology itself at first, and then start lagging behind in a major way later on. When you compare the actual pattern of development and diffusion, as we do in this report, to the hype cycle, it can be concluded that expectations and reality are not synchronised.

The Essay Exploration Quantum Technology (2019) is an example of a first attempt at considering the pros and cons of Quantum technology:
"Quantum technology can lead, for example, to a greater economic equality (between the haves and have-nots), criminal networks that can no longer be monitored (is that desirable?) or drastically changing geopolitical relations (both in economic and in military terms). As such, Quantum technology is generally speaking regarded as a very important strategic asset; by countries, but also by businesses. And the role of Quantum technology in the development of artificial intelligence may also raise issues."
Essay Exploration Quantum Technology (2019), p. 24.

At the moment, social expectations regarding Quantum technology appear to be in the first phase, the so-called hype phase. Potential negative effects of Quantum technology are underexposed and there is little discussion or deliberation regarding the pros and cons of the use of the new technology, apart from the possibility that Quantum computers can crack encrypted messages and may pose a threat to our security and privacy.

Good information and a careful consideration of the interests of all the relevant stakeholders are an important element of the crucial debate about new technology, with which there is ample experience in the scientific domain of "Technology Assessment" (Banta, 2009; Grunwald, 2009; Tran and Daim, 2008), or more recently, "Responsible Innovation" (for example Ortt et al., 2020). For Quantum technology, a cautious discussion has been started among scientists, but the societal debate has yet to commence. This report provides information that can be used in that debate.

Chapter 1

Quantum technologies

and their applications

1

Introduction

Quantum technologies are based on the principles of quantum mechanics. The term Quantum technology is used to refer to different technologies. The UK Defence Science and Technology Laboratory draws a distinction between a first and second generation of Quantum technologies (Dowling and Milburn, 2003). The first generation includes technologies that are used in systems like lasers, transistors and MRI imagers that are based on the principles of quantum mechanics. These technologies have been scientifically researched since the start of the 20th century and have led to products that are ubiquitous. The second generation includes technologies that actively create, manipulate, and observe Quantum conditions. This report is about the second generation of technologies and the products that they enable.

What are Quantum technologies?

Technological principles

Quantum technology is based on various technological principles (see, for example, Spiller and Munro, 2006). We describe those principles on the basis of the size and characteristics of Quantum particles.

58 grams of table salt (with the chemical formula NaCl) is about 6 table spoons of salt, and contains 6*1023 molecules. Each molecule of table salt consists of 2 atoms: a sodium atom and a chloride atom, which in turn consist of subatomic particles, like neutrons, protons and electrons. In addition, other subatomic particles have been discovered by physicists, like Higgs bosons, quarks, etc. Quantum technology is based on subatomic particles.

The size of a Quantum particle
Quantum particles are subatomic particles, which means they are smaller than an atom.

Quantum particles exists on a much smaller scale than the world that is visible with the naked eye. On that much smaller scale, different laws of physics apply. It is the contrast between the world that is visible with the naked eye and the world of Quantum particles that makes the phenomena of Quantum technology so counter-intuitive and difficult to understand.

The characteristics of a Quantum particle
As a metaphor, a marble can be considered a particle in the visible world. It can move with a certain speed in a certain direction. That combination of speed and direction is referred to as momentum. As long as a marble has momentum, it keeps rolling. If you draw a point with a '+' above the marble and one with a '-' underneath the marble and draw an imaginative axis through those points, that axis has a certain orientation, which is referred to as polarisation. In addition, the marble will spin to the left or to the right, which is indicated by the direction and speed in which the marble spins.

A Quantum particle has a certain position (location), a speed in a direction (momentum), an orientation (polarisation), and it spins around an axis with a certain speed (spin). That part of the Quantum world resembles that of the visible world of a marble. But there are differences. In addition to the characteristics of a (hard or massive) particle, a Quantum particle also has the characteristics of a wave.

That mixed wave/particle characteristic has all kinds of wondrous consequences. It is impossible to push a marble with a certain diameter through a hole with a smaller diameter, whereas a Quantum particle can move as a wave through a barrier with a certain likelihood. This is the so-called tunnelling effect.

However, Quantum particles are not pure waves like we see them in our visible world, because those waves have a continuously variable energy, while Quantum particles can only contain certain, 'discrete' amounts of energy. This is the so-called Quantum size effect. You could say that a Quantum particle is a packet of energy with certain discrete values that behaves like a hybrid between a particle and a wave.

> "A Quantum particle is a packet of energy with certain discrete values that behaves like a hybrid between a particle and a wave."

Quantum particles can also be added together like a kind of waves. For instance, sea waves can cancel or reinforce each other, which does not apply to marbles. The addition of waves into a new wave is called superposition. What is special about that is that two waves can move independently in a basin and then blend, creating a new wave that can be bigger or smaller, depending on whether they reinforce or dampen each other. If those waves keep moving, the combined wave once again divides into the two original waves, which means that the information of the two original waves was still present in the combined wave, which is also an important aspect of superposition in the visible world. If you add two possible states of a Quantum particle, the particle retains a certain likelihood of one state and a certain likelihood of the other state. This is the so-called Quantum superposition effect, an effect that is not known in exactly that form in the visible world.

So, Quantum particles are not pure particles or pure waves as we know them in our visible world, for if we measure the location of a Quantum particle, its speed is unknown, which means that it is impossible to know the values of all the above-mentioned characteristics of the Quantum particle at the same time with certainty. This is the so-called uncertainty principle, a principle that is hard to understand. It is an example of the fact that the laws of physics are not the same at a subatomic level as they are in the visible world. Before we can move on to Quantum technology, there are two more aspects of Quantum particles that we need to mention.

Particularities of working with Quantum particles

The first aspect is that Quantum particles are hard to measure. They have all kinds of characteristics that can be measured individually. One of the problems is that measuring a characteristic of a Quantum particle involves interacting with that particle, which means that disturbance occurs. In short, when you measure a characteristic of a Quantum particle, the value of that characteristic changes. That principle also occurs in the visible world. A needle can have a certain temperature, but when you measure the temperature of that needle, it will be much lower than the original temperature, due to the energy that is needed to heat up the mercury that measures the needle's temperature. A similar problem occurs with Quantum particles, which are so small that there are no smaller particles with which you can measure the characteristics of Quantum particles without disturbing them. On the other hand, those Quantum particles are so small and sensitive that they can be used for extremely accurate measurements.

The second aspect of Quantum particles that is crucial for the use in Quantum technology is the so-called entanglement effect. When you create a pair of Quantum particles that are each other's opposites, they are inseparably connected, no matter how far apart they are. And here is what is so hard to understand: if you do separate those two Quantum particles and change the state of one particle, the state of the other particle, which may be on the other side of the world, will also change instantaneously, in a way that ensures that the particles remain perfectly correlated. Einstein theoretically derived that phenomenon, but thought it was impossible and resulted from a theoretical error. He called this phenomenon the 'spooky effect', because he felt that it was impossible for information from one Quantum particle to be transferred to another particle faster than the speed of light. However, the effect has since been demonstrated in experiments several times. The theory was correct and, together with Einstein, we need to accept that this spooky phenomenon is real.

> ”Together with Einstein, we need to accept that this spooky phenomenon is real.”

We have listed the special characteristics of Quantum particles in overview in Table 1-1. The characteristics of the Quantum particles and principles involved are important for understanding the functionality of different Quantum technologies.

Table 1-1: Characteristics and principles of Quantum particles at a subatomic level

Characteristics and principles of Quantum particles	Brief explanation
1 Size	A Quantum particle is a particle at subatomic level that obeys the laws of quantum mechanics that are different from the laws of physics as we know them in our everyday lives.
2 Position	Location of the particle.
3 Momentum	Speed * mass in a direction of the particle.
4 Polarisation	Orientation of the particle.
5 Spin	Spin and direction of the particle around an axis.
6 Mixed wave/particle character	A Quantum particle sometimes behaves like a particle and sometimes like a wave.
7 Tunnelling principle	Quantum particle can pass a barrier with a certain chance.
8 Quantum size principle	Quantum particles can only contain certain (discrete) amounts of energy.
9 Superposition principle	Quantum particle states can be added together like waves, but remain with a certain likelihood in one and the other state.
10 Uncertainty principle	Not all characteristics of a Quantum particle can be determined at the same time.
11 Observer principle	If you conduct a measurement to determine the state of a Quantum particle, that state will be altered.
12 Entanglement principle	A pair of entangled Quantum particles will always maintain interconnected characteristics (instantaneous), no matter how far they are apart.

Functionalities

Functionalities mentioned in literature

Quantum technologies can be used to provide different functionalities. Table 1-2 gives an overview of functionalities of Quantum technologies.

Table 1-2: Functionalities of Quantum technologies

Functionality		Source			
Term in literature	Brief description	Acin et al. (2018)	Spiller and Munro (2006)	Eureka[2]	Physics World[3]
Time-keeping	Super-accurate time measurement				Time-keeping
Sensing and measuring	Super-sensitive measurements	Quantum sensing and metrology	Quantum sensing and detecting	Sensing and metrology	Sensing & measurement
Cryptography	Secure encryption of data		Cryptography		
Key exchange	Sending crypto-graphic key		Quantum Key exchange		
Communication	Secure and fast telecommunication	Quantum communication	Quantum communication	Communication	Secure communication
Computing	Superfast calculations	Quantum computation	Computing		Computing and AI
Simulation	Simulation of complex systems	Quantum simulation	Quantum simulation	Simulation	
Imaging					Imaging
Games Auction			Quantum games Quantum auction		

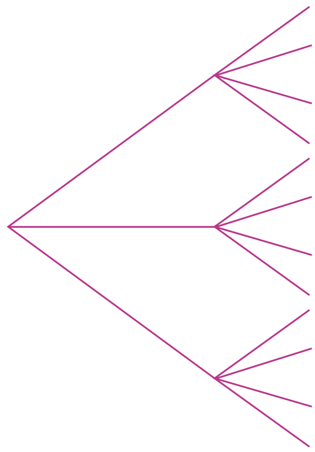
[2] https://www.eurekalert.org/pub_releases/2019-02/ip-etg022119.php

[3] https://physicsworld.com/a/mapping-the-commercial-landscape-for-quantum-technologies/

Functionalities combined and ranked

When those different functionalities are combined and sorted, the result is a tree diagram with different generic and specific functionalities (see table 1-3).

Table 1-3: The tree diagram of Quantum technology

Discipline	Generic functionalities	Specific functionalities	Discipline as tree diagram of functionalities
Discipline Quantum	Measuring/sensing	Measuring time Measuring gravity Measuring magnetism Measuring vibrations	
	Communicating	Cryptography Random number creation Quantum Key distribution Quantum Internet	
	Computing	Computing specific Computing generic Simulation	

The applications of Quantum technologies have not completely crystallised yet. The functionalities are the start of a clear delineation of possible market applications, which are not yet fully known.

Market applications, how do you describe them?
A market application of a technology means that the technology is used in the form of a product or service by a target group of customers in a given context for a given purpose (examples of purposes: meeting a need, solving a problem, ...).

How can Quantum particles provide different functionalities?

To understand Quantum technology (to some degree), it is important to understand how the characteristics and principles of the Quantum particles (see Table 1-1) can deliver that functionality.

Time measurement

A Quantum particle, like an electron, can move around the core of an atom in different orbits. Time measurement uses the principle that electrons can move in different orbits around an atom and that the energy from the transition from one state to another state is released by waves with a very narrowly limited frequency. The measurement of that frequency is then used to determine and define the time unit of the second.

The Cesium-133 atom, for example, emits a frequency of 9192,631770+-0,000020 MHz if an electron changes orbits. When that frequency is measured, it is possible to determine a second as a unit of time very accurately. That means that Quantum technology is able to measure time much more accurately, which is crucial in many day-to-day applications, like the use of GPS systems. Standard GPS is accurate at a distance of +/-2 metres. That is enough to get your sailboat safely into a marina, but clearly not good enough when placing a part of a bridge you are building.

Sensors and measuring instruments

The fact that Quantum particles are very small also makes them very sensitive and therefore suitable to conduct measurements. For instance, Quantum technology can be used to measure gravity, very weak magnetic fields or small accelerations and changes in direction of moving objects with great accuracy. At face value, that does not sound all that interesting, but it is good to realise that being able to measure and observe phenomena often leads to a huge range of new inventions. The microscope, as an accurate measuring instrument, has led to numerous inventions, like detecting bacteria and being able to explain diseases. In science, great leaps are often made when the ability to measure things accurately increases by a factor (Arthur, 2009). As such, Quantum technology can also lead to great innovations. In practical terms, Quantum sensors that measure acceleration or a change of direction, in a different way than through GPS, can also be used to determine where a moving vehicle is located.

Cryptography

Random keys are random or accidental numbers that are generated and then serve as a basis for encrypting a message. For example, the number 2 can serve as a key in which all letters are replaced by letters that are two positions down the alphabet. The word 'alphabet' would become 'cnhcdgy'. For cryptography, it is important for the key (the number) to be truly random and therefore hard to ascertain. Every computer has a random number generator. The problem is that that generator is not truly random, but produces an approximation of a random number, an approximation that can be ascertained by a very powerful computer, which is why it is claimed that the NSA can decrypt encrypted messages because it has very powerful computers[4] (see Bone Castro, 1997, p.02). Quantum technology can be used to decrypt random numbers that are generated by traditional computers, but it can also be used to generate genuinely random numbers and serve as a basis for a safe encryption of data in telecommunication.

Key exchange

Making a cryptographic key is an important step in the safe encryption of data. However, it is important that the key in question is not only available to the sender, to encrypt the message, but also to the recipient, to decrypt the message, which means that the key has to be shared without falling into the wrong hands. Quantum technology can be used to transmit such a key securely. If someone should intercept the key in transit, both the sender and recipient will know, because the key will have changed (see characteristic 11 of Table 1-1). As a metaphor, you could say that the key will bend if it is used by anyone but the intended recipient. If the key is intercepted, you simply do not send the message with the key, but you create another key, until the key reaches its destiny without being intercepted, after which you can send the encrypted message, because both the sender and the recipient will have the key. So Quantum technology can enable data traffic via other communication channels.

Communication

The 'entanglement principle' describes how a pair of Quantum particles can have completely opposite characteristics. It also describes that, if one of the particles is manipulated in a way that changes its characteristics, the other particle, which may be on the other side of the world, will also undergo a change at the exact same moment. That effect means you can send a message with infinite speed. In telecommunication as it exists today, information is communicated with a maximum speed, the speed of light. Quantum technology can do that even more

[4] https://www.businessinsider.com/quantum-technology-2017-7?international=true&r=US&IR=T

quickly, hence the functionality 'communication', which can be a very important application of Quantum technology. Scientists and engineers are already working on a 'Quantum Internet'.

Computing

If you can manipulate Quantum particles to get a finite number of different characteristics, with one particle being manipulated as input and the other one undergoing a similar change as output, that opens up a lot of possibilities. For example making numbers with a large group of particles and performing operations on those numbers and, in essence, building a computer, one that is based on the entanglement principle and on the superposition principles. The functionality of 'computing' can also provide a basis for a large number of different applications. Computing is an important element of a number of other applications listed above, like 'cryptography', 'simulation', 'imaging' and 'gaming'.

Quantum computing makes it possible to make calculations much more quickly than with traditional computers on the basis of bits. Bits can take on the values of '0' or '1', which corresponds to a switch through which a current 'does' or 'does not' flow. If you combine several of those switches, you can make calculations, for instance add numbers. A qubit is different from a bit, because it can take on multiple values at the same time. In Quantum technology, a subatomic particle can represent a superposition of multiple values, which means that, essentially, you can make multiple calculations at the same time, a lot more quickly than you can with existing computers.

Increasing the capacity of computers is, for instance, important in medical science. When developing medications, it is important to be able to determine the exact behaviour of a molecule in the human body. Existing supercomputers can simulate the behaviour of a simple molecule with a maximum of 4 atoms. However, medications often consist of much larger molecules, and to simulate their effect on the human body, or on a virus or bacteria, a Quantum computer will be needed.

Chapter 2

Patterns and factors

of the development and diffusion of Quantum technologies

2

Introduction

This chapter is about the patterns of development and diffusion of individual Quantum technologies. We look at the factors that hamper or stimulate the development and diffusion of Quantum technologies, focusing on the variations of the three basic functionalities of Quantum technology:

1. Measuring and sensor technology, with special attention to the atomic clock.
2. Communication technology, with special attention to cryptography.
3. Computer technology, with special attention to the first generic computer.

The atomic clock and other Quantum measuring and sensor technologies

Definition of the atomic clock technology

The atomic clock measures the time (to be more exact, the length of a second) by using the principle that electrons can move in different orbits around an atom and that the energy of the transition from one state to the next is absorbed and released by a very narrowly limited frequency. The measurement of that frequency is then used to determine and identify the time unit of the second.

The technology of the atomic clock can be defined as follows:

Functionality:
Measuring frequency and measuring time unit.

Technological principle:
Measuring the frequency of waves that are absorbed or emitted when electrons around an atom change orbits. Although different atoms can be used for that, the standard with which the second is measured is the Caesium-133 atom.

Basic components:
Quartz clock and component to measure frequency of transition of electron in atom and then use it to calibrate the Quartz clock.

An atomic clock consists of two main components, the first of which is a highly accurate quartz clock, while the second component measures the frequency that an atom absorbs or emits when electrons change orbits around the atom. The second component as it were calibrates the quartz clock. That second component consists of a number of parts, starting with a part that makes it possible to select atoms in a certain state (often with a magnetic field in a vacuum and extreme cooled state). Those selected atoms are then brought into a disturbed state (using a frequency that oscillates a little around the correct value). The frequency at which the waves are absorbed is exactly the right frequency. The electrons then go back to their basic state, while emitting waves, again with that very specific frequency and it is that frequency that forms the basis for measuring and defining time.

Pattern of development and diffusion of the atomic clock

The exact definition of basic data like the second (time), the metre (distance) and the kilo (weight) were considered important in the US for the general functioning of society, as well as science and industry. That is why the National Bureau of Standards (NBS) was founded in 1901. The NBS also conducted scientific research that formed the basis for various standards. In 1948, the principle of the atomic clock was demonstrated (Forman, 1985; Lombardi et al., 2007; Sullivan, 2001).

The clock was based on the frequency that is emitted or absorbed by ammonia when the electrons change orbits. The first atomic clocks were not used for official time measurements and they were at first less accurate than the then current standard time measurement with advanced quartz clocks. The invention and demonstration of the atomic clock was followed by a long period in which the technological principle was improved incrementally.

In 1956, the first atomic clock was sold as a product, which was manufactured by the 'National Company of Malden' (Natco, for short) and of which about 50 were sold under the product name 'Atomichron'. The clock was big, expensive and unwieldy, but highly accurate. Funding for the development and production of these clocks came mostly from the military and about 90% of the clocks were primarily used for military purposes. In commercial terms, the clock was not a huge success, and Natco went bankrupt in 1969 (Forman, 1985).

In the same period, in 1964, Hewlett-Packard markets an atomic clock, called the 5060, which is the basis for the atomic clocks that were developed so far (Lombardi, 2017). In 1967, worldwide, a time standard is recorded with a Caesim-133 atomic clock. From that moment on, atomic time is used on a grand scale, even though there are only a few atomic clocks. The National Bureau of Standards (NBS), later rechristened the National Institute for Science and Technology (NIST), markets a variety of services. From 1974 on, time is transmitted via geostationary satellites and from the mid-1980s, time is sent along with the GPS signal via other satellites, followed in 1988 by a computer service and in 1993 by an Internet time service. In addition, time is always available via telephone, radio and television.

We view 1967 as the start of the large-scale diffusion of the *use* of 'atomic time', but the large-scale *production and diffusion* of large numbers of atomic clocks starts much later, from about 2011.

Table 2-1: Dates of the pattern for atomic clocks

Year	Event	Source
1948-49	Invention	(Sullivan, 2001; Forman, 1985)
1956	Introduction	(Lombardi et al., 2007)
1964-1967	Start large-scale use of 'atomic time' with small number of clocks.	(Kitching, 2018)
2011	Start industrial production and large-scale diffusion of atomic clocks.	(Kitching, 2018)

Figure 2-1 is a stylised representation of the pattern of development and diffusion on the basis of historical data. It gives an impression of the use of atomic time (the blue dashed line) and the number of atomic clocks (the blue solid line) over time. Figure 2-2 (next page) shows an estimate of the number of atomic clocks for civilian use in the near future. On the basis of our data, Figure 2-1 implies that industrial production and large-scale diffusion started some time ago (from 2011), while Figure 2-2 indicates that the sale of atomic clocks for civilian use is expected to grow tremendously, to about 1 billion clocks in the next 10 years.

Figure 2-1: Pattern of development and diffusion of atomic clocks

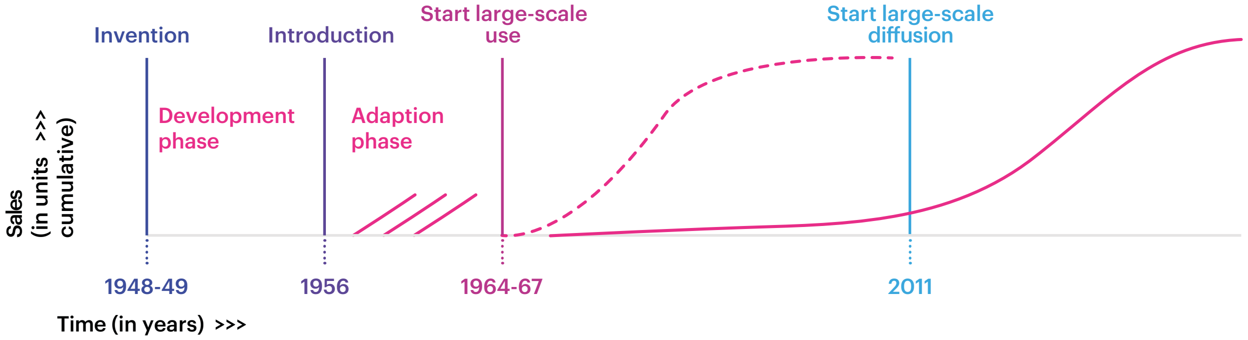
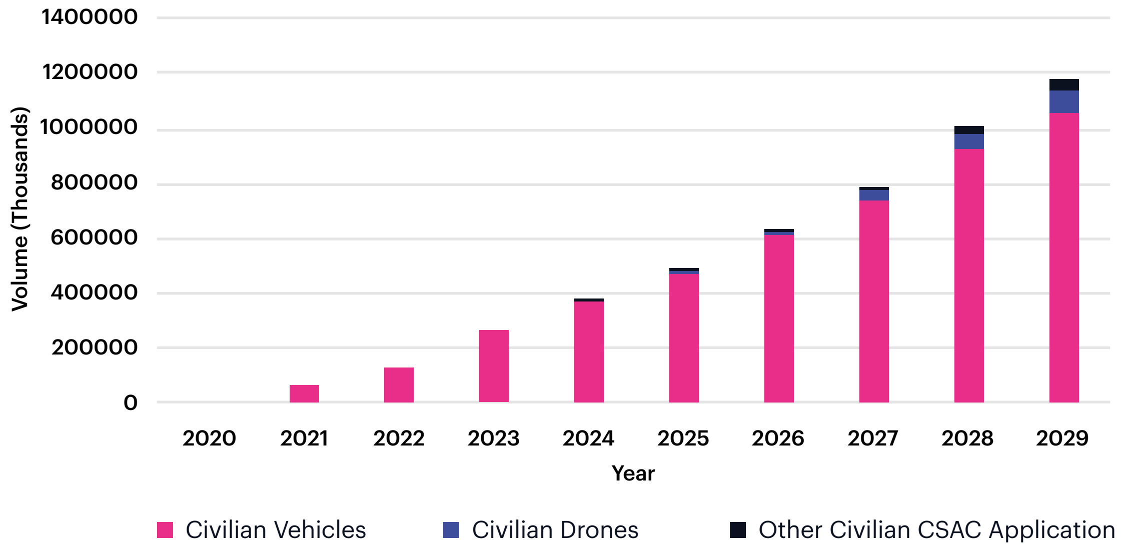


Figure 2-2: sales of atomic clocks for civilian use



https://www.globenewswire.com/news-release/2020/03/09/1997369/0/en/Inside-Quantum-Technology-Report-Shows-Atomic-Clock-Market-Accelerating-Towards-1-billion.html

An interesting detail in Figure 2-2, next to the expected sales growth, is the division of the market for atomic clocks. It is expected that by far the biggest share of the atomic clocks will be used in vehicles, and a much smaller portion in drones and other applications. Clocks in vehicles and drones are used to determine location. Time measurement is crucial in GSP systems, time measurement is also crucial for location determination if GPS is not available or not allowed. The expected numbers are probably higher and the curve begins sooner if you were to include military applications, but that is information that we do not have.

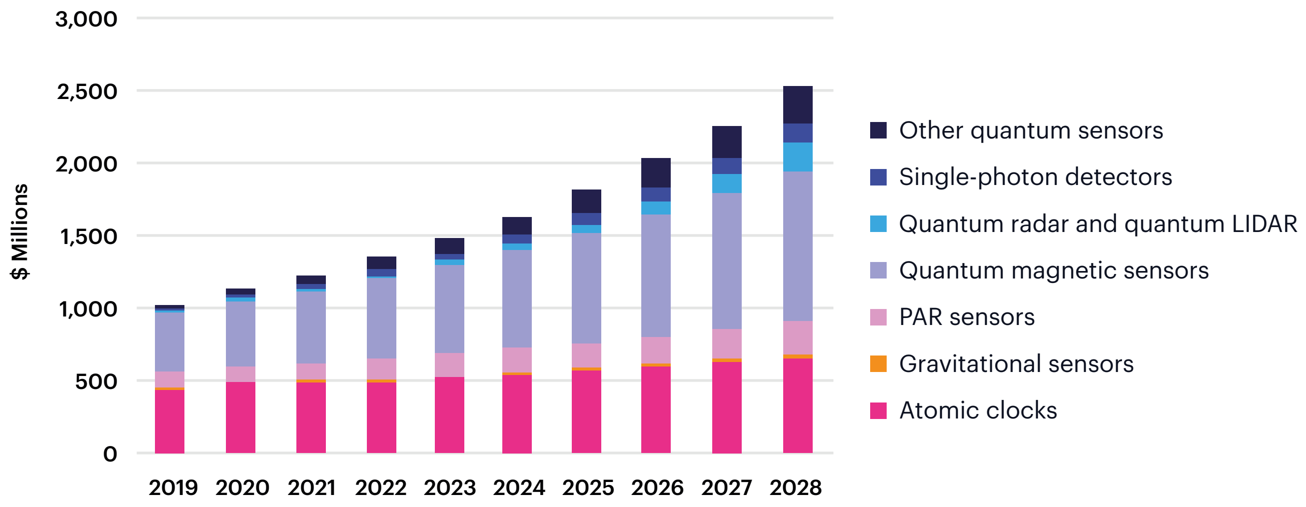
Below Figure 2-2, we see the abbreviation CSAC, which stands for Chip-Sale-Atomic-Clocks. In early 2000, it became possible to make chip-sized atomic clocks. Research and development of such clocks in the US was initially primarily for military purposes. The chips became so small and cheap that they became available to determine the location of soldiers on the battlefield, for drones and even for disposable projectiles. In 2011, followed by a commercial civilian introduction of these CSAS's, which means that atomic clocks are available on chips that can be used in a variety of different systems. As such, smaller atomic clocks have been commercially available on a large scale since 2011 (Kitching, 2018).

Other Quantum measuring and sensor technologies

The atomic clock is the start of a series of related technologies with which very accurate measurements can be made. The atomic clock is extremely accurate, but at the same time highly sensitive to the minutest of deviations or disturbances. Disturbances can be caused by variations in the gravity in different locations on Earth, but also by electromagnetic fields (like the Magnetic North Pole), or by accelerations and changes in direction of a platform on which the atomic clock is standing. Those disturbances are annoying when it comes to measuring time, but can be very useful when the aim is to measure the disturbances themselves.

In addition to the time measurements, then, there are a number of related technologies based on Quantum technology to measure the exact gravity or magnetic fields. Such measurements are important for scientific work. The exact measurement of accelerations or changes in directions, on the other hand, is important for systems that determine the exact position of airplanes and other vehicles, in addition to the use of GPS. As such, these measurements are important to our daily lives. Figure 2-3 gives an estimate of the future market for Quantum sensor technology.

Figure 2-3: predicted sales of Quantum sensors



https://www.insidequantumtechnology.com/51544829_754765628238106_4068148771723149312_n/

This figure indicates that there are various markets for Quantum sensor technology, depending on the specific functionality. The atomic clocks, gravitational sensors and magnetic sensors are obvious examples. A PAR sensor measures photosynthetic active radiation. Photosynthesis takes place in plants when they use light energy to turn carbon dioxide into carbohydrates, like glucose, releasing oxygen. These sensors are used, for example, in agriculture.[5] A photon detector (single photon detectors) measures the presence of minimal packets of light (photons). Photon detectors have been marketed commercially by various companies[6].

At the moment, the markets for atomic clocks and for gravitational measurements are the biggest, but according to these predictions, other applications of the sensors are slowly emerging as well. In addition to the relative size of the different markets, the figure also reflects a sequence of the applications of Quantum technology. The atomic clock was the first application, but it was quickly followed by the magnetic and gravitational sensors, and then by other applications such as Quantum radar.

[5] *https://www.nieuwkoopbv.nl/nl/product/par-sensor-lp471par/*

[6] *https://www.idquantique.com/quantum-sensing/products/id230/?gclid=Cj0KCQjw9ZzzBRCKARIsANwXaeKhLfZaeHJ84oQh5-3Aily-jom0Yxb4Vs8fbkOxCuF1rOt_pyvY8gwaAi6AEALw_wcB*

Hampering and stimulating factors for Quantum measuring and sensor technologies

The atomic clock is used on a large scale and has been perfected over the years, as can be seen in the dashboard of all the relevant technological, social and market-related factors that can hamper or stimulate development and diffusion, all of which have been set to green for some time now, with the possible exception of the core factor product price: atomic clocks are not cheap, but these days are available for about € 1.000[7], while PAR-sensors cost about € 400. Quantum systems are mostly sold in professional markets.

Table 2-2: Factors for Quantum measuring and sensor technologies[8]

Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary products and services		11 Financial resources	
5 Actors and network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	

Explanation of the Table:
(1) The factors are defined and their use is explained in Appendix 1, in which the method of the technology monitor is listed.
(2) A green colour means that the factor has a positive influence or does not hamper the large-scale application and diffusion of the technology. Yellow means that the factor has both negative and positive effects, and red means that the factor hampers the large-scale application and diffusion of the technology.

[7] https://www.electronicdesign.com/technologies/analog/article/21806867/cant-afford-an-atomic-clock-get-a-molecular-one

[8] *Apart from this Table, we do not divide the data further. We will do so in the case of Quantum communication and Quantum computing, because those technologies still face considerable barriers to large-scale diffusion.*

Quantum cryptography and other Quantum communication technologies

Definition of the Quantum communication technology

Quantum communication is a collection of technologies that enable superfast and secure forms of (tele)communication. In the future, there could be a Quantum Internet, with lightspeed communication that is completely secure.

There are various principles of Quantum communication. A first principle is the transmission of quantum particles via fibre optic cable or light beams through the air (also known as 'line-of-sight') in which certain characteristics of the particle, like its spin, are used to transmit information at the speed of light. A second principle is the transmission of information via connected particles based on the entanglement principles (also known as teleportation).

In practice, telecommunication via telephony, satellites or the Internet requires all kinds of components that together make up a communication system, including peripherals (tablets, PCs, mobile phones), a network, circuits and amplification to transmit the signal across huge distances. That also indicates how interconnected Quantum computing and Quantum communication are. The problem is that not all of those components can already be made with or for Quantum technology. In the case of the first principle (transmitting Quantum particles through fibre optic cable or through the air), the problem is that those particles are very sensitive to their environment, which means that an amplifier or circuit that is required to rout the information from user one to user two also causes disturbance of the information. In the case of the second principle, the problem is that the two connected Quantum particles are stable for a very short time only, which means they can only be used for that short time. That is the reason that specific components of the communication system are made and delivered using Quantum technology in a hybrid combination with existing communication systems. Throughout history, a hybrid combination of old and new technology has often been used to introduce new technology incrementally, for example the first freight ships at the start of the 20th centuries, which had both an engine and sails, and modern cars with hybrid propulsion. The hybrid strategy can be a logical strategy for introducing a new technology if the infrastructure surrounding the old technology can be reused for the new technology. In the case of Quantum technology, that is very smart, because not all of the components of a complete Quantum communication system are available and because it is very costly to build a completely new system and persuade people to use that system.

Definition of Quantum cryptography technology

One of the first components of the communication system to use Quantum technology is cryptography, which involves the encryption of data in order to transmit it securely from sender to recipient without other people being able to access or change the information undetected. We look at two components of cryptography: (1) the random number generator used to generate a key with which the data is encrypted, and (2) the transmission of that key from the sender to the recipient of the message in question.

The technology of Quantum cryptography can be defined as follows:

Functionality:
Securing data traffic and telecommunication.

Technological principle:
A Quantum number generator is used to make a Quantum Key with which data is encrypted that is shared between sender and recipient.

Basic components:
- Random number generator to make a Quantum Key (QK);
- Network for sending a Quantum Key (QKD).

Cryptography is a vast domain and one of the main principles is that a random number generator is used to generate a key with which data is encrypted. In practice, however, many random number generators in computers are not truly random; they approximate a random number generator with a certain algorithm[9]. That means that a very powerful computer can be used to break that algorithm and the existing encryption of the data, and that data traffic is no longer secure. Quantum technology on the one hand can lead to computers with which existing encryption keys can be decrypted, and on the other hand to create a true random number generator and generate a so-called Quantum Key (QK) that is impossible to decrypt. There are parties that offer free online Quantum random number generators[10].

A weak link in the use of that generator, assuming that it is truly random, is of course communicating the resulting key over the Internet, which brings us to the second component of cryptography. When a sender encrypts his data with the use of a random number generator, the resulting key needs to be transmitted to the recipient of the message, otherwise the recipient will not be able to decrypt the encrypted message. The key can be transmitted over the same communication channel as the encrypted message, but that makes it easier to intercept, which is why it is better to transmit the key via

[9] *This has also been discussed in the previous chapter, in paragraph 2.2.*
[10] *See, for example: http://qrng.anu.edu.au/index.php*

another channel, because the key is crucial for the security of the data traffic. If you send the key using Quantum communication (so separate from the encrypted message), it can be sent in a secure manner.

Why is that step secure when it involves Quantum communication? Quantum communication is based on the so-called entanglement principle. Two connected subatomic particles, even when they are at a distance of each other, have interconnected characteristics and retain those characteristics when the distance between them is increased (Acin et al., 2018). So if the sender changes something in one particle, the recipient of the other particle can notice that, and that is how you can communicate. In addition, that communication is also based on the principle that observation of a particle changes its state, the so-called observer principle. So if someone were to intercept and read the information in the particle, the other particle also changes, making it clear that the information has been intercepted. So the transmission of the Quantum Key is protected from interception.

There are various possible configurations to enable Quantum Key Distribution (QKD). It can be done using laser technology via satellites, or via fibre optic networks. At the moment, it is important to create good repeaters (amplifiers) and allow switching of communication channels, so that QKD does not have to take place via separate dedicated connections. The problem is, however, that repeaters and switches influence the qubits and, in doing so, distort the information. At the moment, scientists and engineers are working hard on creating repeaters and switches.

Pattern of development and diffusion of Quantum cryptography

The idea, the invention and further development
The idea for using Quantum technology for communication was suggested in 1968 by scientist Stephen Wiesner in a conversation with his collegue and friend Charles Bennet (Broadbent and Schaffner, 2016). Wiesner suggested the idea that Quantum technology could be used for communication and for creating a new kind of money (cryptocurrency) (Brassard, 2006).

Both for communication and for creating money, it is important that a code can be generated that is protected against theft. The difference between money and communication is that, in the case of money, that code has to be stored securely, while for communication, the code is transmitted from sender to recipient. Wiesner's idea was a way to generate such 'secure' codes. In the further development of Quantum technology, the transmission of information via Quantum technology turned out to be easier than storing the information for a longer period of time, which may be the reason why only one of Wiesner's ideas was initially worked out in greater details. But keep in mind: once we succeed in creating a secure and stable Quantum memory, Wiesner's other idea may be picked up again as well.

Wiesner then tried to get his ideas published in the early 1970s in an article with the name 'Conjugate coding', but his article was refused (ultimately to be published ten years later: Wiesner, 1983). Bennet kept thinking about his friend's second idea and discussed it about 10 years later with Brassard on a conference. At that time, Bennet was working at IBM, while Brassard was working at the University of Montreal (Gisin et al., 2002). Together, they worked out the ideas for Quantum communication within a few hours and later published them (Bennet et al., 1982). Their idea initially was met with scepticism, but after creating an experimental set-up in 1989 and demonstrating QKD in practice, there is growing interest. The set-up shows how photons (small packets of light) can be polarised in different ways, making it possible to send information via the photons. Next, the polarised photons are transmitted across a distance (at the speed of light). If anyone intercepts the photons with the information, the state of the photons is changed and the information corrupted. This Quantum communication set-up demonstrates the first principle of Quantum communication, transmission of quantum particles at the speed of light. In short, the set-up is a demonstration of secure Quantum communication. We consider that demonstration as the invention. The whole story was later written down by Brassard in a hugely entertaining article (Brassard, 2005; 2006).

This principle generates secure communication at the speed of light. That communication can be used in different ways. First of all, it can be used to send a complete message securely. Secondly, the communication can be used just to send the key with which information that is send via a different channel can be encrypted by the sender and then decrypted by the recipient. Because Quantum communication is rather elaborate, and because the technology is still in its early stages and it is difficult to send huge amounts of data, the second option is the most frequently used. The key is sent via a different channel than the encrypted message. The encrypted message itself can be sent as usual via the Internet, because the data is worthless without the key. One of the advantages is that the key can be sent prior to the message. If the key arrives intact, you can then also use it to send the message securely. In this process, you *prevent* your message from being intercepted, instead of concluding it after the fact.

A few years later, Ekert (1991) suggested using entanglement to share information between connected particles instantaneously (instead of with the speed of light). The information of one connected

Parties that offer or develop Quantum communication and cryptography products
Aurea Technologies, Crypta Labs, Fujitsu Electric, HP Enterprises, IBM, Infineon, ISARA, MagiQ, Microsoft, Mistubishi, NEC, Nokia, NTT, Nucrypt, Oki, Post-Quantum, QuantumCTek, Quantum Xchange, Qasky, Qinetik, Qubitekk, Quintessance Labs, QuNu Labs, qutools, Raytheon, SeQureNet, Toshiba, Universal Quantum Devices and ZTE.
https://www.24-7pressrelease.com/press-release/439317/quantum-encryption-market-to-reach-25-billion-revenues-by-2022-mobile-systems-will-ultimately-dominate

Quantum particle is passed on at once to the other particle across a distance. This idea means that it is no longer necessary to send photons (or light) via a vacuum of fibre optic cable. This principle is explained in detail by Bennett, Brassard and colleagues (Bennett et al., 1993), who use the term 'teleportation'. The Quantum Key that is needed to securely encrypt the data can now be shared across a large distance, as long as there are two connected Quantum particles. This idea is demonstrated in 1997 (Bouwmeester et al., 1997). That demonstration can be seen as the invention of the second principle of Quantum communication. After all, the technological principle of this teleportation technology is different than that of sending information in Quantum particles via photons or light.

The first applications of Quantum cryptography on the basis of principle 1

There are commercial market reports that indicate that governments and the military were the first customers of Quantum cryptography after 2000[11]. We date the first applications around 2002 (at any rate between 2000 and 2005). Those military applications were not commercial and the data are hard to verify. It was not before 2010 that a small university spin-off with the name ID Quantique would market a commercial Quantum cryptography product[12]. Although, according to the company's website, their market for Quantum cryptography is global, the actual size of the market is still limited, which means it is something of a niche application, at least at the time of its introduction in 2010.

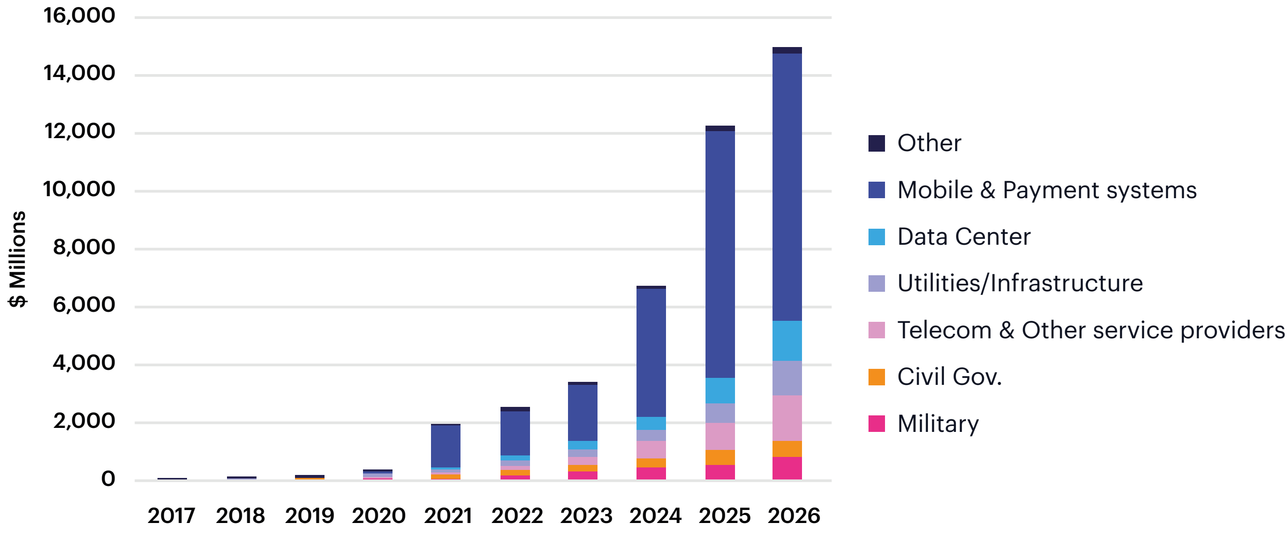
Large-scale diffusion of Quantum cryptography on the basis of principle 1

It is hard to determine whether or not the large-scale diffusion of Quantum cryptography has started. There are several indicators that suggest that the large-scale diffusion has already begun or is about to begin. First of all, in recent years, there has been an increase in the number of publications (a measure of the amount of research) and patents (a measure of the amount of applied research). In addition, there are many companies that are active in Quantum communication (see text in purple) and those are not just start-ups like the abovementioned ID Quantique, but also large companies like IBM, Toshiba, Fujitsu, NEC, Nokia, NTT, Raytheon and HP. What is also interesting is that those companies come from a variety of sectors, providing military communication and navigation technology (like Raytheon), telecommunication (like NTT and Nokia) and computer systems (like IBM, HP and NEC).

[11] *https://www.24-7pressrelease.com/press-release/439317/quantum-encryption-market-to-reach-25-billion-revenues-by-2022-mobile-systems-will-ultimately-dominate*

[12] *From 2010 onwards, IDQ rolled out quantum-safe crypto solutions in both commercial and government markets worldwide. https://www.idquantique.com/*

Figure 2-4 Predicted turnover for Quantum Key Distribution (QKD)



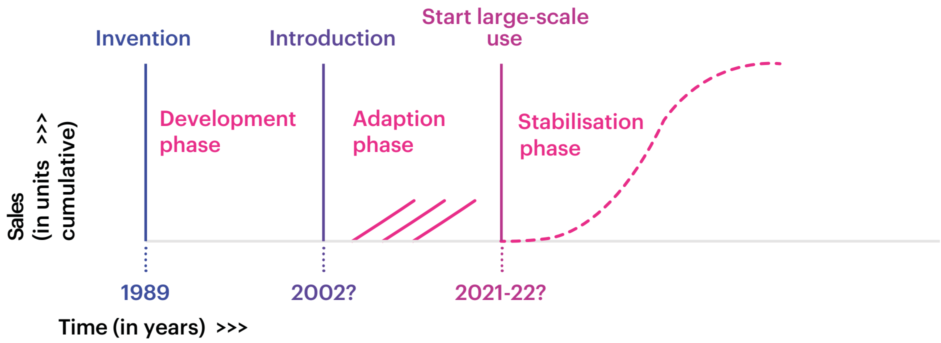
https://www.24-7pressrelease.com/press-release/439317/quantum-encryption-market-to-reach-25-billion-revenues-by-2022-mobile-systems-will-ultimately-dominate

Figure 2-4 gives an indication of the relative size of different submarkets that will use Quantum Key Distribution (QKD). The largest market consists of companies offering mobile payment services. Figure 2-4 also points to a specific order of applications or user groups during the development of the market, starting with military users and then governments, followed by a list of civilian user groups for which secure data communication is crucial, like companies offering mobile and payment services, telecommunication companies and data centres.

Table 2-3: Data of the Quantum communication cryptography pattern (principle 1)

Year	Event	Length of phases		Source
1989	Invention	Development	+/- 13 years	(Brassard, 2005, 2006)
2002 (between 2000-2005)	Likely initial (military) applications	Adaptation	+/- 20 years	
2010?	Introduction on the civilian market	Adaptation	+/- 20 years	See footnote 8
2021-22?	Start industrial production and large-scale diffusion	Stabilisation		Own observation based on indicators

Figure 2-5: Pattern of development and diffusion of Quantum communication cryptography (principle 1)



The first applications of Quantum communication on the basis of principle 2 (teleportation)

Teleportation refers to the instantaneous transmission of an object (so faster than the speed of light). In the context of Quantum technology, teleportation means that *information* is transferred instantaneously, not matter, as is often depicted in science fiction. Teleportation has been demonstrated in experiments with photons, but also with atoms and molecules, and the phenomenon has also been measured across increasingly large distances, even across more than 1000 km (Pirandilo et al., 2015).

The importance of teleportation with Quantum technology is immense, because Quantum teleportation can play an important role in all three basic functionalities of the Quantum discipline, namely measuring and observing, communicating and computing.

At the moment, no actual applications of teleportation are known, other than experimental installations in different locations around the world. That means that, after its invention in 1997, Quantum teleportation continues to be in its development phase. It is unclear when the first market introduction will take place and the adaptation phase begins.

Hampering and stimulating factors for Quantum communication

Overview of the factors

Table 2-5: Factors for Quantum communication

Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary products and services		11 Financial resources	
5 Actors and network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	?

Explanation of the Table:
(3) The factors are defined and their use explained in Appendix 1, in which the method of the technology monitor is listed. The information required to determine the role of the factors is included in Appendix 2.

(4) A green colour means that the factor has a positive effect or does not impede large-scale application and diffusion of the technology. Yellow means that the factor has both positive and negative effects, and red means that the factor impedes large-scale application and diffusion of the technology.

The overview of the hampering and stimulating factors indicates that, although considerable progress has been made regarding all the core factors that are needed to construct a system surrounding Quantum communication, none of those factors is actually complete, which is the reason that Quantum communication is not yet applied on a large scale. The causes of that are clearly visible in the list with influencing factors. The knowledge of the technology and the availability of people with knowledge of Quantum technology are limitations.

It is also noteworthy that the social debate about the sociocultural aspects of the technology has barely begun and that hardly any accidents, unexpected events or abuse have been reported. The latter two are closely connected. Our analysis does indicate, however, that for specific Quantum communication technologies, like Quantum Key Distribution, large-scale diffusion is likely in a few years.

The Quantum computer

Definition of the Quantum computer technology

The definition of the technology of the Quantum computer includes three aspects: the functionality, the technological principle and basic components that make up the technology.

Quantum computers use quantum-mechanical effects in a smart way. Superposition and entanglement play an important role in that, which makes them function in a fundamentally different way than traditional computers. A traditional computer uses bits, which can be 0 or 1. A Quantum computer uses qubits (an abbreviation of 'quantum bits'), which can be 0 and 1 at the same time, in other words, they can be in a superposition of 0 and 1. The qubits of a Quantum computer can collectively be in a superposition of all possible states. By having the computer operations performed on qubits, in theory multiple calculations can be carried out at the same time, as is illustrated by the text box about the Quantum computer versus the traditional computer. Because they can perform multiple operations simultaneously, Quantum computers can potentially solve problems that are virtually impossible to solve on traditional computers, because the calculations would take exponentially more time.
(National agenda Quantum technology, 2019, p.21)

Functionality

The functionality of a computer is to carry out operations. That is a very broadly defined functionality, and there are many different types of computers. There are computers that only perform very specific calculations, and there are more generic multifunctional computers that, depending on the software, support a wide variety of functionalities.

Technological principles

The National agenda Quantum technology gives a short description of the technological principles of a Quantum computer.

Basic components of a Quantum computer

The basic components of a Quantum computer, in addition to the usual peripheral equipment, are a memory for both data and software, a processor and an operating system. The processor is the most central component for using Quantum technology.

Configurations

Quantum computers exist in all kinds of configurations and variations. A Quantum computer can, for example, be a hybrid combination with a traditional processor. That means that the Quantum processor is only used for those calculations that cannot be performed by the traditional processor (see National Agenda Quantum technology, 2019, p. 24). There are different technological platforms of Quantum computers: (1) so-called 'ions traps' (also known as superconducting qubits); (2) 'Quantum dots in silicon' or (3) topological Quantum computers. Companies are working on different platforms. IBM and Google are working on the first type of platform, Intel is working on the first as well as the second type of platform, and Microsoft is working on the third type of platform (see National agenda Quantum technology, 2019, p. 27).

Pattern of development and diffusion of the Quantum computer

The idea, the invention and the introduction

The first idea of the Quantum computer is often attributed to professor Feynman (Bone Castro, 1997, p. 2). His idea, expressed in 1981 at a lecture at MIT, was that that computer would be so powerful that it would even be able to simulate the Quantum phenomena themselves. In 2020, so 40 years after his prediction[13], 'ordinary' supercomputers are able to simulate molecules with about four atoms with all their subatomic effects. A Quantum computer would be so powerful that it could simulate the behaviour of much larger molecules. The dating of the idea of the Quantum computer is striking when we realise that, as early as 1970, Wiesner had the idea of using Quantum technology for secure communication and for cryptocurrencies. At that time, Wiesner was unknown and his publication about the subject was rejected, while Feynman was a famous physicist with a Nobel prize (which he was awarded in 1965).

The idea of the Quantum computer was then worked out in different stages by various people. The principles of the Quantum computer were described one by one. The principle of a Quantum computer was first demonstrated in 1998 by Isaac Chuang of the Los Alamos National Laboratory, Neil Gerschenfeld of MIT, and Mark Kubinec of UC Berkeley[14].

Twenty years later, in 2017, IBM presented the first commercially usable Quantum computer[15]. IBM offers calculating capacity on the computer and the principle of the Quantum computer is explained, as well as how interested users can make a programme for the Quantum computer themselves[16]. Google also built a Quantum computer and claims that that computer is much faster than existing supercomputers, which created a discussion, because that claim is denied by IBM[17].

The introduction date of 2017 may be an estimate that is years behind the genuine first application of the Quantum computer. In 2017, IBM's Quantum computer was made commercially available, but it is quite possible that the Quantum computer was used earlier than that for military and government purposes, which would mean that the introduction date was much earlier as well. However, there is no information available to confirm that hypothesis.

Large-scale diffusion?

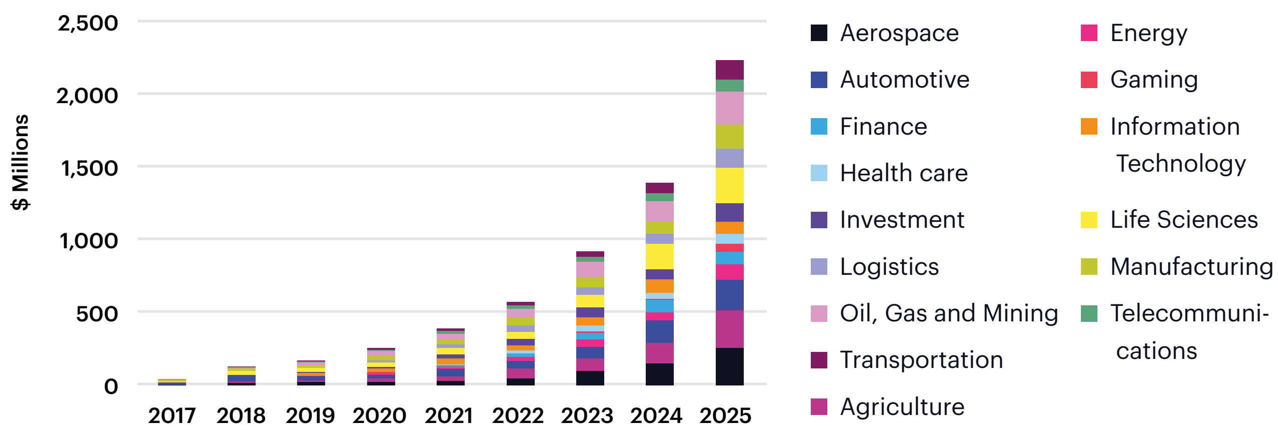
Similar to Quantum communication, and in particular cryptography, it is hard to indicate whether or not large-scale diffusion has already begun, but there are indicators. The fact that multiple large companies (including Intel, Microsoft and Google) are already investing heavily in Quantum computing could mean that the start of large-scale distribution is near or already behind us. But these large companies are still working on different types of Quantum computers. There is as yet no dominant form or standard for the Quantum computer. There will, of course, be different types of Quantum computer for different applications, but such a division of the market is not yet visible. We expect that the start of a large-scale diffusion will be somewhat later than that for Quantum cryptography, as can be seen in the estimation of the market size for cryptography (see above) in 2021 of US$ 2 billion, compared to about US$ 400 million for the market for Quantum computing in 2021.

13 https://pursuit.unimelb.edu.au/articles/a-brief-history-of-quantum
14 https://www.britannica.com/technology/quantum-computer
15 https://medium.com/@markus.c.braun/a-brief-history-of-quantum-computing-a5babea5d0bd
16 https://www.ibm.com/quantum-computing/
17 https://www.rtlz.nl/tech/artikel/4895646/google-quantumcomputer-intel-quantumsuperioriteit

Table 2-6: Data of the pattern of the Quantum computer

Year	Event	Length of phases		Source
1998	Invention	Development	19	Britannica[18]
2017 or sooner	Introduction	Adaptation	?	
?	Start industrial production and large-scale diffusion	Stabilisation	?	

Figure 2-6: Prediction of the turnover for Quantum computing per industry (worldwide)



https://tractica.omdia.com/newsroom/press-releases/enterprise-quantum-computing-market-to-reach-2-2-billion-by-2025/

It is interesting to note the variety in the markets for the Quantum computer, especially compared to the number of applications for the Quantum technologies we discussed earlier. That is understandable, because computers are a generic technology that already play an important role in almost all industries. It is also noteworthy that there is no single largest application, unlike the technologies discussed earlier (Quantum measuring and sensor technology and Quantum communication technology).

[18] https://www.britannica.com/technology/quantum-computer

Hampering and stimulating factors for the Quantum computer

Overview of the factors

Table 2-7: Factors for Quantum computer

Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary products and services		11 Financial resources	
5 Actors and network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	?

Explanation of the Table:
(5) The factors are defined and their usage explained in Appendix 1, in which the method of the technology monitor is explained. The information needed to determine the role of the factors is included in Appendix 2.

(6) A green colour means that the factor has a positive effect or does not impede large-scale application and diffusion of the technology. Yellow means that the factor has both positive and negative effects, and red means that the factor impedes a large-scale application and diffusion of the technology.

What stands out in this overview is the fact that all the core factors that are needed to create a complete ecosystem surrounding Quantum computing need to be complemented. Quantum computers are technologically possible, as a principle, but there are as yet no practical operational systems that make large-scale diffusion possible. In that sense, Quantum computing technology lags behind Quantum Key Distribution, as part of Quantum communication. That is largely due to a lack of knowledge of the technology, for instance how to increase the number of qubits of a Quantum computer and how to make sure that qubits can remain stable long enough. The development and diffusion of Quantum computing is also impeded by a lack of qualified people to develop, build and operate Quantum computers. In addition, the social debate about the sociocultural effects of Quantum computing has yet to get started. The application of Quantum computing is as yet so limited that there have hardly been any negative or unexpected effects, abuse, accidents or unexpected events. When that changes, that is sure to fan the social debate.

Conclusion and discussion

What stands out is that the various Quantum technologies are in very different phases of the pattern for development and diffusion. In this report, we use a model of that pattern with three consecutive phases: development, adaptation and stabilisation. Time measurement with Quantum technology is a technology that has been the standard for time measurement, so that technology is well within the stabilisation phase, while Quantum communication, in particular cryptography, is probably about to break through and is therefore in the transition between adaptation and stabilisation.

We think that, as far as Quantum computing is concerned, large-scale application is unlikely to happen until a few years into the future. The technology is still in the middle of the adaptation phase, in which various experimental computer versions are only used in specialised market niches by a very limited number of business customers and governments.

It is interesting to see that the atomic clock has been in the stabilisation phase for years and that atomic clocks are sold in great numbers, especially since atomic clocks can be put on a chip. And while everyone thinks that Quantum technology is still an experimental technology, it has been the standard technology for telling the time for half a century. The large-scale diffusion of time measurement using Quantum technology really took off with the introduction of time measurement on a chip in 2011. In the wake of time measurement, Quantum technology is also often used in sensor and measuring equipment. So the different technologies of the discipline are in different phases. While one Quantum technology has become commonplace virtually unnoticed, other Quantum technologies, that are still in an experimental phase, have received much more publicity.

To explain the difference concerning the phases in the pattern of development and diffusion in which the different Quantum technologies find themselves, we can look at the history of the development and diffusion, which is what we have done in this report. We can also look at impeding and stimulating factors, which we also did in this report, using a framework with 14 factors. The list of impeding and stimulating factors is designed in particular to indicate the extent to which the system of actors and factors surrounding the technology in an emerging market are complete enough to allow large-scale diffusion of that technology to occur. In the early stages of new markets, when the initial products based on a new technology are sold and used, many of those factors are often incomplete. In that situation, organisations can decide to introduce the technology in specific product variations and niche applications that are often highly different from later products and large-scale applications. That is not always because those later large-scale applications are unknown, but above all because those applications are not yet possible with the limited development of the market system or the current state of the technology at that point.

Chapter 3

Conclusions

3

Introduction

In this chapter, we summarize the answers to the research questions:

1. What are Quantum technologies?
2. What is the pattern of development and diffusion of the Quantum technologies and what is their current position in that pattern?
3. What are the factors that hamper or stimulate the further development or diffusion?

In the final paragraph, we provide practical recommendations.

Answers to the research questions

What are Quantum technologies?

Quantum technology is a collection of technologies in which the characteristics of particles like electrons are used and manipulated at a subatomic level, so inside atoms. We distinguish three functionalities: (1) the measurement of time, gravity and magnetism; (2) communication and cryptography and (3) computer processing.

Quantum technology is a discipline that consists of a number of different technologies that are still considerably interwoven and in which the individual technologies to a limited extent show their own pattern of development and diffusion.

What is the pattern of the Quantum technologies and their current position?

Below, we present the most important dates for the three Quantum technologies we have examined.

Table 3-1: the pattern of the three Quantum technologies

	Quantum time measurement and sensors	Quantum cryptography and communication	Quantum computing
Invention	1948	1989	1998
First application	1956	2002	2017
Start large-scale use	1967	2020-2021?	-

Of all the applications, the atomic clock is the most advanced in terms of the pattern. It was invented as early as 1948, its first applications appeared in 1956 and large-scale diffusion of the use of the atomic clock began around 1967, when the atomic clock became the global standard for the exact measurement of time. At the time, the number of atomic clocks was limited, but it did become the standard for the time measurement used everywhere. After 2011, the number of atomic clocks also increased when they became available on chips. Cryptography and Quantum communication followed later, and we expect that their large-scale diffusion is near. Quantum computing will start even later, and we expect it will be some years before their large-scale diffusion.

It is noteworthy that the time between invention and initial application increases steadily for the three consecutive technologies (from 8 years for the atomic clock, 13 years for Quantum communication to 19 years for Quantum computing). The time between initial introduction and large-scale application also appears to increase (from 11 years for the atomic clock, to 18-19 years for Quantum communication. The time interval is unknown yet, for the Quantum computer). It is interesting to see that Quantum computing is receiving a lot of attention, while that version of Quantum technology is the least advanced. The maturity of the Quantum technologies appears to be inversely proportional to the attention they receive.

What are the factors that hamper or stimulate further development or diffusion?

In the report, we look at fourteen factors that can impede the further development and diffusion of Quantum technology. Together, those factors form a dashboard. For each factor, we used the colour green (no impediment for large-scale diffusion), yellow (partial impediment for large-scale diffusion) and red (serious impediment for large-scale diffusion) to indicate what the effect is for further development and diffusion. The level of impediment, of course, varies over time, some barriers are removed in the course of time. We have mapped the state of the barriers at this point in time, in 2020. In the table below, we list the results for the three Quantum technologies.

Table 3-2: an overview of the impediments of the Quantum technologies

Core factors	Measuring, sensing	Communication	Computing
1 Product performance	green	yellow	red
2 Product price	yellow	yellow	red
3 Production system	green	yellow	yellow
4 Complementary products and services	green	yellow	yellow
5 Actors and network formation	green	yellow	yellow
6 Customers	green	yellow	yellow
7 Standards, rules and laws	green	yellow	yellow
Influencing factors	**Measuring, sensing**	**Communication**	**Computing**
8 Knowledge of technology	green	yellow	red
9 Knowledge of applications	green	green	green
10 Employees and resources	green	yellow	yellow
11 Financial resources	green	green	green
12 Macroeconomic and strategic aspects	green	green	green
13 Sociocultural impeding factors	green	yellow	yellow
14 Accidents and unexpected events	green	?	?

There are a number of things that stand out when we look at the impediments for the three Quantum technologies.

First of all, there are the 'empty' factors. The possible negative side-effects of technology (like accidents and other unexpected things), have been insufficiently examined. In light of the enormous social interest of the technologies, that is an important issue.

The technologies show a very different picture. The atomic clock has hardly any barriers to speak of anymore, even the price has gone down now that there are atomic clocks available on a single chip. Things are different for Quantum communication and computing. Technically speaking, there is still a lot of work to do: the performance has to be fast and reliable, the large-scale production systems needed to deliver the technology have yet to be built and there are still only a few complementary products and services. From a market perspective, many of the networks of actors who will develop, manufacture and deliver the technologies have yet to be formed. Customers lack the knowledge that is necessary to be able to use the technologies. Values, rules and laws have not yet been adjusted. The large-scale use of the technologies requires all kinds of certificates, tests and institutions that monitor if things are going well. In that area, there is still a lot to do. This phenomenon also occurred with earlier technologies that were examined with the framework of the technology monitor.

Practical recommendations

In this paragraph, we start by looking at the practical recommendations for the three Quantum technologies for organisations, after which there will follow some general recommendations.

Practical recommendations Quantum measuring and sensor technology

Quantum technology appears to be a distant thing for many people and organisations. However, that is a misconception. Our time has been set by atomic clocks for many years now, we use GPS technology on a daily basis, and it has been based on this time measurement for decades. Quantum sensors used to measure magnetic fields, gravity or changes of direction of a moving object have also been available for years. For those organisations for which such sensors are part of the core process, now is the time to learn more about this technology, because the products based on the technology are becoming cheaper and smaller, making them available on a large scale.

Practical recommendations Quantum communication

The misconception that it will take a long time for a broad application of Quantum technology to occur seems relatively harmless when you look at the atomic clock. However, that misconception becomes dangerous when you talk about Quantum communication and computers. Have a look at the text at the right (from 2015!!).

Quantum computers make our current technology to encrypt data and then transmit them via the Internet or other channels, unsafe. The first Quantum computers are available via the web. Quantum computers are available on the market. We are now waiting for the first hacks of normal secured data traffic. When that can happen (on a massive scale) is hard to assess. In the quote below, it is indicated that it can still take a few years. However, in the abovementioned quote, it is made clear that it will happen very quickly.

The exact date on which Quantum computers are useful to decipher normal secured data is actually not important if data that are securely encrypted now, are stolen and stored until such time as the data can be deciphered. In practice, we would argue that any organisation that wants to transmit important information and exchange it with customers securely, needs to work out how its data can be transmitted securely in the near future as well.

That can be done, for example, using the following steps:

1. Not only look at the current data, but also at the time period that data needs to be secured. Encrypted data can be stolen before the encryption key is available. If Quantum computers that can be used to find the key at a point when the information is still sensitive and important become available later, stealing and storing information now, that cannot yet be decrypted, can be worthwhile.

2. Learn more about available Quantum cryptography technology or methods that use cryptography keys that cannot even be broken by Quantum computers, so-called post-Quantum cryptography.

3. Determine which actions are needed at a certain state of the technology. Follow the state of technological development.

At the same time, today's security technologies are not keeping up with the sophistication of modern-day hackers, as well as advanced technologies, such as quantum computing. The US National Security Agency (NSA) recently advised US agencies and businesses that all email, medical and financial records, and online transactions, will soon be vulnerable to quantum computing technology threats, and that today's encryption technologies will not protect them in the future. As a result, the NSA has announced plans to move to quantum-resistant algorithms for greater protection in the future. ***(article from 2015-09-29) http://www.convergenceasia.com/story/acronis-partners-id-quantique-bring-quantum-safe-encryption-cloud***

It is impossible to give a good estimate of when Quantum computers will be powerful enough to break encryption. Estimates vary from 2025 to 2040. One issue is the so-called 'store now decrypt later' scenario: malignant people storing encrypted information now, with the aim of breaking the encryption once Quantum computers have become powerful enough. ***Essay Exploration Quantum Technology (2019), p.18.***

Practical recommendations Quantum computing

In the somewhat longer term, Quantum technology may have very positive effects on the development in domains where calculations so far could not be performed, for example the development of molecules for medication in the pharmaceutical industry.

It is important for organisations that (want to) perform calculations with supercomputers to keep an eye on the development of Quantum computers. Quantum computers are available via the Internet, which offers a cheap way to acquaint oneself with this new technology.

The first Quantum computers that can perform these calculations on a small scale are already available. It is expected that the development of more powerful computers will go quickly.

Companies that focus on materials, chemical substances or medications are recommended to explore the possibilities of Quantum computers in the short term.
Soon, more powerful (and more accurate) Quantum computers will be able to simulate the interaction between substances in the human body, making it possible to manufacture customized medications. Furthermore, so-called metamaterials can be simulated as well: materials with qualities that we do not know from natural materials and substances (de Ingenieur, 2019): think of invisible materials, even better lenses, material that absorbs and transforms sound and light in new ways. Metamaterials can generate change in all sorts of areas, from the car industry (new frames) to the energy sector (superconductors at room temperature or more efficient solar panels). The associated innovations for healthcare, the energy sector and material research will also affect other sectors.
Essay Exploration Quantum Technology (2019), p.35.

General recommendations

Organisations and governments will be faced with quick developments in the area of Quantum technology in the near future. There are a number of things they can learn about Quantum technologies to allow them to decide quickly once the technology reaches a certain state (see below).

There are a number of things that organisations and companies can learn about Quantum technologies now:

- → Learn about technology to understand the possibilities it offers or understand the potential threats involved.
- → Monitor the state of the technology over time, for instance using the instruments of the technology monitor.
- → Identify what the possible effects of Quantum technology are on the core processes of the organisation.
- → Map actions to utilise or limit the impact of those future effects.
- → Determine when (at a certain state of the technology or the market) which actions are needed, for instance using the indicators formulated in our framework.
- → Monitor the development and diffusion of Quantum technologies over time.

The government plays an important role in funding research and development, and in creating an ecosystem that brings together all the complementary parties that are needed to develop and market Quantum technology. That is already happening.

Because the government is also dealing with large amounts of sensitive data, it has to prepare itself for the consequences of Quantum technology for its own organisation. That means, for example, that the government can provide a central department with information and advice for (government) organisations.

Quantum technologies are an enormous breakthrough with potentially huge social consequences. It will be interesting to monitor how the various Quantum technologies will develop and diffuse and which policies and strategies turn out to be effective to stimulate this technology!

Sources

References

Acín, A. et al. (2018). The quantum technologies roadmap: a European community view New J. Phys. 20 080201

Al Natsheh, A., Gbadegeshin, S. A., Rimpiläinen, A., Imamovic-Tokalic, I., & Zambrano, A. (2015). Identifying the challenges in commercializing high technology: A case study of quantum key distribution technology. Technology Innovation Management Review, 5(1).

Arthur, W. B. (2009). The nature of technology: What it is and how it evolves, Simon and Schuster.

Banta, D. (2009). What is technology assessment?. International journal of technology assessment in health care, 25(S1): 7-9.

Bennett, C.H., Brassard, G., Breidbart, S. and Wiesner, S. (1982). "Quantum cryptography, or Unforgeable subway tokens", Advances in Cryptology: Proceedings of Crypto '82, Santa Barbara, Plenum Press, pp. 267 – 275, August 1982.

Bennett, C.H., Brassard, G., Crépeau, C., Jozsa, R., Peres A., and Wootters, W.K. (1993). "Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels", Physical Review Letters 70(13), pp. 1895 – 1899.

Bone, S., & Castro, M. (1997). A brief history of quantum computing. Imperial College in London.

Bouwmeester, D., Pan, J-W., Mattle, K., Eibl, M., Weinfurter, H. and Zeilinger, A. (1997). "Experimental quantum teleportation". Nature. 390 (6660): 575–579.

Brassard, G. (2005). "Brief history of quantum cryptography: A personal perspective", Proceedings of IEEE Information Theory Workshop on Theory and Practice in Information Theoretic Security, Awaji Island, Japan, pp. 19 – 23,October 2005.

Brassard, G (2006). Een aangevulde versie of bovenstaand artikel is te vinden via *https://arxiv.org/pdf/quant-ph/0604072v1.pdf*

Broadbent, A., & Schaffner, C. (2016). Quantum cryptography beyond quantum key distribution. Designs, Codes and Cryptography, 78(1), 351-382.

Dedehayir, O., & Steinert, M. (2016). The hype cycle model: A review and future directions. Technological Forecasting and Social Change, 108, 28-41.

De Touzalin, A., Marcus, C., Heijman, F., Cirac, I., Murray, R., & Calarco, T. (2016). Quantum manifesto. A new era of technology. European Comission.

Dowling, J. P., & Milburn, G. J. (2003). Quantum technology: the second quantum revolution. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 361(1809), 1655-1674.

Ekert, E.K. (1991). Quantum cryptography based on Bell's theorem, Physical Review Letters 67(6), pp. 661 – 663.

Essay Exploration Quantum Technology; Aanbevelingen ter voorbereiding op een gezamenlijke toekomst met quantumtechnologie (2019). Uitgegeven door: Platform voor de InformatieSamenleving. *https://ecp.nl/wp-content/uploads/2020/04/Essay-Verkenning-quantumtechnologie.pdf*

Forman, P. (1985). The first atomic clock program: NBS, 1947-1954. SMITHSONIAN INSTITUTION WASHINGTON DC.

Gisin, N. Ribordy, G. Tittel, W. and H. Zbinden, "Quantum cryptography," Rev. Mod. Phys. 74, pp. 145–195, Mar 2002.

Grunwald, A. (2009). Technology Assessment: Concepts and Methods. Philosophy of Technology and Engineering Sciences: 1103-1146.

Kitching, J. (2018). Chip-scale atomic devices. Applied Physics Reviews, 5(3), 031302.

Lombardi, M. A., et al. (2007). "NIST primary frequency standards and the realization of the SI second." NCSLI Measure 2(4): 74-89.

Lukkien, C. (2020). Voorkomen is toch beter dan genezen? Een onderzoek naar kansen en uitdagingen voor preventieve gezondheidszorg. Door Frisse Blikken in opdracht of STT. Stichting Toekomstbeeld der Techniek (STT), Den Haag.

National agenda Quantum technology (2019). Uitgegeven door: Quantum Delta Nederland. *https://www.nwo.nl/actueel/nieuws/2019/09/nationale-agenda-quantum-technologie-nederland-internationaal-centrum-quantumtechnologie.html*

Ortt, J. R. (2010). Understanding the Pre-diffusion Phases. Gaining Momentum Managing the Diffusion of Innovations. J. Tidd. London, Imperial College Press: 47-80.

Ortt, J. R., of Putten, D., Kamp, L. M., & of the Poel, I. (Eds.). (2020). Responsible Innovation in Large Technological Systems. Routledge.

Pirandola, S., Eisert, J., Weedbrook, C., Furusawa, A., & Braunstein, S. L. (2015). Advances in quantum teleportation. Nature photonics, 9(10), 641.

Riedel, M. F., Binosi, D., Thew, R., & Calarco, T. (2017). The European quantum technologies flagship programme. Quantum Science and Technology, 2(3), 030501.

Rogers, E.M. (2010). Diffusion of innovations. Simon and Schuster.

Spiller, T. P., & Munro, W. J. (2005). Towards a quantum information technology industry. Journal of Physics: Condensed Matter, 18(1), V1.

Sullivan, D.B. (2001). "Time and frequency measurement at NIST: The first 100 years". 2001 IEEE International Frequency Control Symposium. NIST. pp. 4–17.

Tran, T. A., & Daim, T. (2008). A taxonomic review of methods and tools applied in technology assessment. Technological Forecasting and Social Change, 75(9): 1396-1405.

Vermaas, P., Nas, D., Vandersypen, L., Elkouss, Coronas, D. (2019). Quantum Internet; The internet's next big step. TU Delft. *https://pure.tudelft.nl/portal/files/56766989/quantum_20magazine_20june_202019.pdf*

Wiesner, S. (1983). Conjugate coding. ACM Sigact News, 15(1), 78-88.

Overview consulted sites

Chapter 2

1. https://www.eurekalert.org/pub_releases/2019-02/ip-etg022119.php
2. https://physicsworld.com/a/mapping-the-commercial-landscape-for-quantum-technologies/
3. https://www.businessinsider.com/quantum-technology-2017-7?international=true&r=US&IR=T
4. https://en.wikipedia.org/wiki/Quantum_technology

Chapter 3

5. https://www.globenewswire.com/news-release/2020/03/09/1997369/0/en/Inside-Quantum-Technology-Report-Shows-Atomic-Clock-Market-Accelerating-Towards-1-billion.html
6. https://www.insidequantumtechnology.com/51544829_754765628238106_4068148771723149312_n/
7. https://www.nieuwkoopbv.nl/nl/product/par-sensor-lp471par/
8. https://www.idquantique.com/quantum-sensing/products/id230/?gclid=Cj0KCQjw9ZzzBRCKARIsANwXaeKhLfZaeHJ84oQh5-3Aily-jom0Yxb4Vs8fbkOxCuF1rOt_pyvY8gwaAi6AEALw_wcB
9. https://www.electronicdesign.com/technologies/analog/article/21806867/cant-afford-an-atomic-clock-get-a-molecular-one
10. http://qrng.anu.edu.au/index.php
11. https://www.24-7pressrelease.com/press-release/439317/quantum-encryption-market-to-reach-25-billion-revenues-by-2022-mobile-systems-will-ultimately-dominate
12. https://www.idquantique.com/
13. https://pursuit.unimelb.edu.au/articles/a-brief-history-of-quantum
14. https://www.britannica.com/technology/quantum-computer
15. https://medium.com/@markus.c.braun/a-brief-history-of-quantum-computing-a5babea5d0bd
16. https://www.ibm.com/quantum-computing/
17. https://www.rtlz.nl/tech/artikel/4895646/google-quantumcomputer-intel-quantumsuperioriteit
18. https://tractica.omdia.com/newsroom/press-releases/enterprise-quantum-computing-market-to-reach-2-2-billion-by-2025/

Chapter 4

19. http://www.convergenceasia.com/story/acronis-partners-id-quantique-bring-quantum-safe-encryption-cloud

Appendices

20. https://www.technologyreview.com/s/612964/what-is-quantum-communications/
21. https://en.wikipedia.org/wiki/Quantum_key_distribution
22. https://www.photonics.com/Articles/Chip-Based_Quantum_Key_Distribution_Could_Secure/a65655
23. https://www.ncsc.gov.uk/whitepaper/quantum-security-technologies
24. https://www.toshiba.eu/eu/Cambridge-Research-Laboratory/Quantum-Information/Quantum-Key-Distribution/Toshiba-QKD-system/
25. https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf
26. https://thequantumdaily.com/2020/03/06/now-hiring-the-quantum-hr-challenge/
27. https://www.theguardian.com/technology/2019/aug/02/quantum-supremacy-computers
28. https://www.theverge.com/circuitbreaker/2017/1/25/14390182/d-wave-q2000-quantum-computer-price-release-date
29. https://www.hpcwire.com/2019/09/24/d-waves-path-to-5000-qubits-googles-quantum-supremacy-claim/
30. https://www.quora.com/How-much-does-a-quantum-computer-cost;
31. https://en.wikipedia.org/wiki/Quantum_computing
32. https://thequantumdaily.com/2020/03/06/now-hiring-the-quantum-hr-challenge/

Appendices

The Technology Monitor 2020

Quantum Technology

Appendix 1
The Technology Monitor as a method

The Technology Monitor maps the development and diffusion of a technology. The method consists of three interrelated components:

1. The definition of the technology, to make it clear what it is exactly that is being mapped.
2. The general pattern of development and diffusion of a technology, to make it clear how the technology has developed and what its current state is.
3. The system of factors that play an important part in the development and diffusion of the technology, to be able to indicate which factors impede or stimulate the further development and diffusion.

Each of the three components provides a model or simplification of reality and is therefore based on assumptions. The assumptions themselves are not discussed in this brief description.

The definition of a technology

A technology can be defined on the basis of three aspects:

1. **The technological principle**
2. **The functionality**
3. **The components**

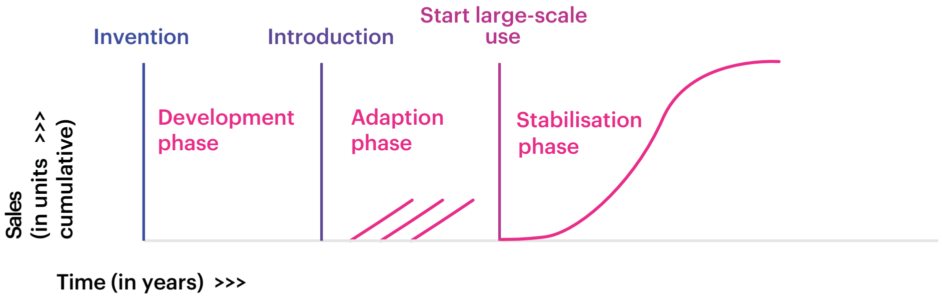
A solar cell is based on the photo-voltaic principle (technical principle). It consists of two types of semi-conductors close to each other (main components) that, when struck by light or other radiant energy, produce an electrical voltage or current when connected by a conducting wire (extra component). The cell can continue to provide voltage and current autonomously i.e., without external power source, as long as light continues to fall on the two materials. This current can be used to measure the brightness of the incident light or as a source of power in an electrical circuit, as in a solar power system (functionality).

The technological principle indicates the principle of the operation, the functionality indicates what you can do with the technology and the components make up the basic elements of the technology. See text in purple for an example of a definition of a technology, the solar cell.

The pattern of development and diffusion of a technology

The 2018 Technology Monitor by STT contains a model that is a realistic representation of the development and diffusion of a technological breakthrough over time (see figure A1-1).

Figure A1-1: the more realistic pattern of development and diffusion of technological breakthroughs



In the pattern of development and diffusions, three important moments in time are distinguished:

1. The invention: the first demonstration of the operation of the technological breakthrough.
2. The first market introduction: the first time the technological breakthrough is sold and applied.
3. The start of the industrial production and large-scale diffusion and application of the technological breakthrough.

With these important moments, the three consecutive phases can be distinguished:

1. **The development phase:**
   This phase runs from the invention to an initial introduction of products on the basis of the technological invention. The invention is the demonstration of a working principle that often is not yet ready to be manufactured and marketed. In the development phase, research takes place to improve the principle and there are often one or more development trajectories designed to make a product on the basis of the principle that can be sold and applied.

2. **The adaptation phase:**
   This phase runs from the first introduction to the start of production and large-scale diffusion of products on the basis of the technology. This phase often involves a trial-and-error process in which different product versions are introduced in various market niches. Adaptation takes place between the product, different customer groups and different applications. That adaptation can ultimately lead to a standard product. Innovation of products, (production) processes and research into improvement of the technology keep going on as before during this phase.

3. **The stabilisation phase:**
This phase begins with industrial production and large-scale diffusion. It starts with a standard product that can be manufactured on a large scale and that is applied and sold on a large scale. The product versions and applications have at this point stabilised. Often, the innovation of products, processes and research to improve the underlying technology will keep going as before.

The *pattern* is a generic model within which, in practice, the length of the phases can vary considerably. The average length of the development phase is about 10 years, and a similar length has been established for the adaptation phase (see Ortt, 2010). Each phase can be skipped or be longer than average. There are technologies where both the development and adaptation phase took only a year (for instance in the case of dynamite) and there are technologies where those phases take a century (for instance in the case of the fax). The pattern can stop or be interrupted at every stage. The pattern provides the basis for a large number of scenarios that can occur in practice.

The factors that hamper development and diffusion

The pattern of development and diffusion of technological breakthroughs provides a *description* of the process of development and diffusion. It does not provide an *explanation* why that pattern occurs in a specific shape. We are looking in particular for explanations that indicate why the first two phases in the pattern, the development phase and the adaptation phase, sometimes cost very little time and sometimes a lot of time.

We have compiled a list of **general** factors that are needed for the large-scale diffusion of technological breakthroughs. When those factors are in place, they can stimulate the development and diffusion, when they are absent or incomplete, they can be a barrier. The factors are divided into fourteen categories. Seven categories make up the social, economic and technological system: the **core factors**. The other seven factors can affect the core factors or provide an explanation for the impediment on those core factors. This collection of factors represent a considerable expansion of the factors that Rogers (2010) uses to explain diffusion in the standard innovation-diffusion model. Table A1-1 describes the seven core factors that need to be in order to enable large-scale diffusion.

Table A1-1: Core factors for large-scale diffusion of technological breakthroughs

Core factors	Description
1 Product performance	A product (with all components and software) with a sufficiently good performance and quality (in absolute terms or relative to competing products) is needed for large-scale diffusion. A poor performance, quality or unintended side-effects of, or accidents with products can impede large-scale diffusion.
2 Product price	The price of a product includes financial and non-financial investments (for instance time and effort) to obtain and use a product. A product (with all its components and software) with a reasonable price (in absolute terms or relative to competing products) is needed for large-scale diffusion. A high price can impede large-scale diffusion.
3 Production system	A production system that can deliver large quantities of products of sufficient quality and performance (in absolute terms or relative to competing products) is needed for large-scale diffusion. A lack of such a production system, unintended side-effects of, or accidents during production can impede large-scale diffusion.
4 Complementary products and services	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and disposal of products are needed for large-scale diffusion. A lack of or incompatible system components, unintended side-effects of, and accidents with complementary products and services can impede large-scale diffusion.
5 Actors and network formation	Availability of necessary actors and sufficient coordination of the their activities for the development, production, distribution, adoption, use, repair, maintenance and disposal of products are necessary for large-scale diffusion. Coordination can be emergent or implicit (for instance the market mechanism) or it can be formal and explicit (for instance an industry association). If certain actors or coordination mechanisms are necessary but lacking, that can impede large-scale diffusion.
6 Customers	Customers are needed for large-scale diffusion. Customers must have knowledge of the product and its use, and they need to want to have, be able to afford and want to use the product. If there are no customers, that will impede large-scale diffusion.
7 Standards, rules and laws	Standards, rules and laws in relation to the product, production, complementary products and services, or how actors (on the supply and demand ends of the market) must handle the product and the surrounding socio-technological system are needed for large-scale distribution. The absence of standards, rules and legislation can impede large-scale diffusion.

The **core factors** make up a complete system surrounding a new technology. If one or more of those factors are absent or incomplete, or if there is insufficient coordination between the factors, that will impede large-scale diffusion.

The **influencing factors** can explain why one or more of the core factors are incomplete, absent or do not fit. As such, these influencing factors explain problems in the system of core factors and give an indication of (future) changes in the core factors. In other words, the influencing factors can explain impediments in the core factors and show changes in those core factors (see Table A1-2).

Table A1-2: Influencing factors for large-scale diffusion of technological breakthroughs

Influencing factors	Description
8 Knowledge of technology	This includes fundamental and applied knowledge of the technology. Fundamental knowledge has to do with technological principles involving the product, production, complementary products and services and knowledge for the development (design), production and management of technological principles. If relevant actors are lacking technical knowledge that is vital to their role, that can impede large-scale diffusion.
9 Knowledge of applications	This includes knowledge of potential applications, knowledge of the market (structure) and the actors involved. This knowledge is needed by all actors, including customers, in order to formulate strategies and product requirements, and to find other actors. If relevant actors are lacking knowledge of applications that is relevant to their role, that can impede large-scale diffusion.
10 Employees and resources	The availability of employees with the necessary knowledge and skills and the availability of resources and input like components and materials are needed for the production and usage of a product, for production, complementary products and services. Organisations that play a role in managing these aspects, like trade unions, are also included. A lack of such resources can affect the core factors and thus impede large-scale diffusion.
11 Financial resources	Financial resources and the organisations (for instance banks) or platforms (for instance crowdfunding) to deliver these resources are needed for the development and diffusion of new products, production systems, complementary products and services, and for the adoption, implementation and maintenance of the products. A lack of financial resources among actors on the demand or supply end of the market (two important core factors) can impede large-scale diffusion.
12 Macroeconomic and strategic aspects	Macroeconomic and strategic aspects refer to the general economic situation in a country or industry, like a recession or industry-wide stagnation. Strategic aspects refer to the interests of countries and industries. Macroeconomic and strategic aspects of countries and industries can affect the core factors and thus impede large-scale diffusion.
13 Sociocultural aspects	Sociocultural aspects refer to the norms and values in a certain culture or industry. They include methods and habits in a country or industry and can also refer to interest groups outside of the supply chain. These aspects tend to be less formalised than formal standards, laws and rules. Sociocultural aspects can influence the core factors and thus impede large-scale diffusion.
14 Accidents and unexpected events	This includes accidents and events outside of the socio-technological system with a major impact, like wars, nuclear accidents, natural disasters and political revolutions. These accidents and events, or the risk of them occurring, can influence the core factors and thus impede large-scale diffusion.

An example indicates why that combination of core factors and influencing factors is so important. If a core factor is missing, for instance because there are no consumers, large-scale diffusion is impossible. Consumers are an important core factor, one that can be influenced by various factors. For instance, consumers can lack knowledge regarding the technology and its applications (influencing factors 8 and 9) or the technology can be too expensive for the consumers (influencing factor 11). Each of the influencing factors has a different effect on the core factor 'consumers' and therefore requires a different policy from regulatory organisations or governments, or a different strategy from organisations wanting to market the technology.

Appendix 2

Information about conditions of Quantum technology

Information about the conditions of Quantum communication

1. **Product performance**
The distance along which Quantum communication can take place is limited by the lack of secure and reliable repeaters of the signal direction[19] (Vermaas et al., 2019). In addition, the routing of signals from one or more senders to various other recipients is also difficult (Essay Exploration Quantum Technology 2019, p. 40). In practice, Quantum communication has started generating and sending Quantum Keys (QKD) with which data can be encrypted and send via ordinary communication channels. As a result of the absence of repeaters and switches, there are also limitations that apply to the transmission of those Quantum Keys.

2. **Product price**
At the moment, Quantum Key Distribution (QKD) is still expensive[20], but large companies are working on prototypes of less expensive systems[21].

3. **Production system**
There are several small companies that have been offering QKD solutions for a number of years. Bigger companies are now working on providing QKD solutions on a larger scale (see footnote 21).

4. **Complementary products and services**
Many complementary products and services are still lacking. New software is needed and new hardware has yet to be developed, like reliable Quantum memories in which a lot of information can be stored for a longer period of time. In addition, protocols and rules are needed to integrate all the complementary products and services (Riedel et al., 2017; Al Natsheh et al., 2015).

[19] https://www.technologyreview.com/s/612964/what-is-quantum-communications/
[20] https://en.wikipedia.org/wiki/Quantum_key_distribution
https://www.photonics.com/Articles/Chip-Based_Quantum_Key_Distribution_Could_Secure/a65655
https://www.ncsc.gov.uk/whitepaper/quantum-security-technologies
[21] https://www.toshiba.eu/eu/Cambridge-Research-Laboratory/Quantum-Information/Quantum-Key-Distribution/Toshiba-QKD-system/

5. **Actors and network formation**
Governments of different countries bring parties together to develop and apply Quantum technology, for example the EU's Flagship initiative, which helps to coordinate the activities of research institutes and companies. The Quantum manifesto is an important declaration of intent by a large number of scientists and companies in Europe operating in the field of Quantum technology[22] (De Touzalin et al., 2016). Roadmaps have been created in the EU and the US to provide direction to the activities of all the different actors. All these initiatives make initiatives in the development phase transparent and available. However, groups of companies are still working on different standards, which means that, when it comes to marketing the technologies, there is a lot of fragmentation (Al Natsheh et al., 2015).

6. **Customers**
There are still many small and fragmented niche markets and knowledge among potential customers about Quantum communication is still limited (Al Natsheh et al., 2015).

7. **Norms, rules and laws**
In the area of technology certification and standardisation, there is still a lot of work to be done, which is understandable, because certification and standardisation require the technology to have a certain level of maturity. If the technology is not yet stable and changes continuously, standardisation and certification are difficult. In addition, government regulation has a slowing effect, next to all the stimulating initiatives that governments start (Al Natsheh et al., 2015; Essay Exploration Quantum Technology, 2019, p. 41; Riedel et al., 2017).

8. **Knowledge of technology**
The knowledge of the technology increases with tremendous speed through the ample funding and coordination of technology development in different parts of the world. But the knowledge is as yet insufficient to create a complete Quantum Internet. As a result of the current knowledge of the technology, components of a future Quantum Internet are now used in a hybrid combination with the existing Internet.

9. **Knowledge of applications**
For Quantum Key Distribution (QKD), the functionality is available in niche markets. In addition, both in the US and in the EU, roadmaps have been set up for Quantum communication. The knowledge of the applications does not appear to impede the further development and diffusion of Quantum communication or QKD.

10. **Employees and resources**
There is a huge shortage of employees with the right knowledge about Quantum technology[23].

11. **Financial resources**
Huge budgets are available in China, Russia, the US and in Europe (Acin et al., 2018).

12. **Macroeconomic and strategic aspects**
Quantum communication and computing, and all the associated technology, is of strategic scientific, economic and military value, which is why the major global powers are working hard on Quantum technology.

[22] https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf
[23] https://thequantumdaily.com/2020/03/06/now-hiring-the-quantum-hr-challenge/

13. Sociocultural aspects

So far, virtually no attention has been paid to sociocultural aspects of Quantum technology. In many technical articles, it is mentioned that privacy is guaranteed with Quantum communication, but that that privacy also provides toom to terrorists and criminals. The sociocultural aspects are slowly entering the scientists' field of vision (see, for instance, Vermaas et al., 2019), but the societal debate about the desirability and consequences of Quantum technology has not yet started, which means that the effect of the sociocultural aspects on the development and diffusion of Quantum communication technology is hard to assess. The 'Essay Exploration Quantum Technology' (2019) provides an agenda for the debate in which sociocultural and societal effects are tabled.

14. Accidents and unexpected events

There is (almost) no information about accidents with Quantum communication technology[24].

[24] A search in Google scholar with the keywords 'accident' and 'Quantum communication' (in the title of sources) results in zero hits. If the terms are used in general, there are many hits, but they relate to 'by accident' instead of 'accidents'.

Information about the conditions of Quantum computing

1. **Product performance**
Quantum systems are extremely unstable and sensitive to disturbances. To maintain their Quantum behaviour, Quantum-but chips need to be locked in a kind of vacuum box that is cooled to a temperature close to absolute zero, which means it is as yet unclear whether bigger systems with lots of Quantum-bits can ever be made stable for a longer period of time to allow them to function[25]. In addition, Quantum-bits are sensitive to noise, which means that wrong answers will be generated, for which error corrections will be developed, but they in turn use extra Quantum-bits. Building a large-scale and universal Quantum computer is a challenge that will probably require a lot of technological breakthroughs[26]. What is interesting is that a company called D-wave already has marketed a computer that, it claims, contains 2000 Quantum-bits[27], in addition to which a 5000 Quantum-bit computer has been announced[28]. Furthermore, since the autumn of 2019, there has been a lot of discussion about the question whether Quantum computers are much faster than 'ordinary' supercomputers. This is also known as Quantum supremacy[29]. We conclude that the product performance does not allow for a large-scale diffusion in the short term.

2. **Production system**
It is estimated that a Quantum computer factory will cost about US$ 100 million[30]. As yet, there are no factories for large-scale production, and it is unknown how many Quantum computers the company D-wave manufactures exactly.

3. **Complementary products and services**
Microsoft develops Quantum algorithms that can be applied on different platforms, and the company is working on a programming language (National agenda Quantum technology, 2019). In addition, people are working hard on developing different kinds of Quantum memories that are both efficient (so that no information is lost) and scalable (Acin et al., 2018, p. 5). However, there are still many barriers to be overcome with regard to complementary products and services, for example developing software that can be checked (debugged), something that is not possible right now, and the development of intuitive user interfaces, specifically for Quantum computers.

4. **Actors and network formation**
On the supply side of the market, parties are involved in developing Quantum technology. In addition to a large number of research institutes across the world, large companies like Intel, IBM, Google and Microsoft are also involved in development. That means that things are speeding up. There are experiments involving many different systems, which increases the likelihood of a well-functioning system being developed or of dedicated systems for different applications being formed by all those parallel research trajectories. Large-scale diffusion is impeded, however, because of a lack of technical standard or dominant type of Quantum computer.

[25] *https://www.theguardian.com/technology/2019/aug/02/quantum-supremacy-computers*

[26] *This and other technological challenges are discussed at length in the National agenda quantum technology, 2019, p. 27-30.*

[27] *https://www.theverge.com/circuitbreaker/2017/1/25/14390182/d-wave-q2000-quantum-computer-price-release-date*

[28] *https://www.hpcwire.com/2019/09/24/d-waves-path-to-5000-qubits-googles-quantum-supremacy-claim/*

[29] *https://www.hpcwire.com/2019/09/24/d-waves-path-to-5000-qubits-googles-quantum-supremacy-claim/*

[30] *https://www.quora.com/How-much-does-a-quantum-computer-cost*

Unlike in the development phase, large-scale diffusion requires limited variety. Another barrier with regard to network formation is that essential components like special cables or important complementary products like Helium-3 can only be supplied by a limited number of companies[31].

5. **Customers**
There are groups of customers who are the first to be interested in Quantum computers, like governments, military organisations and specialised research and development companies. However, at the moment, there are fragmented niche markets and there is an enormous lack of knowledge among potential customers.

6. **Standards, rules and laws**
There are different technological platforms of Quantum computers: (1) so-called 'ions traps' (also known as superconducting qubits); (2) 'Quantum dots in silicon' and (3) topological Quantum computers. Different companies work on different platforms (see National agenda Quantum technology, 2019, p. 27). So there is no standard yet, which complicates things, because all kinds of peripheral devices depend on the platform involved, which means that further development and diffusion can slow down because of parallel platforms (National agenda Quantum technology, 2019). Furthermore, there are also no rules and laws yet governing the use of Quantum computers.

7. **Knowledge of technology**
Technologically speaking, a lot of knowledge that is needed for a complete system surrounding Quantum computers is lacking.

8. **Knowledge of applications**
The knowledge of important applications for Quantum computers is beginning to form. Governments and military organisations, but also, for example, specialised research institutes in the pharmaceutical industry are examples of market applications and users.

9. **Employees and resources**
There is a lack of qualified people for the development of Quantum technology in general, and for Quantum computing in particular[32].

10. **Financial resources**
In different parts of the world, huge funding is available for the development of Quantum computers (Acin et al., 2018).

11. **Macroeconomic and strategic aspects**
In macroeconomic and strategic terms, Quantum computing is considered to be extremely important, which is why all major powers in the world are investing massively in Quantum technology (Acin et al., 2018).

12. **Sociocultural aspects**
The societal debate about the desirability and consequences of Quantum technology in general has yet to get underway, which means that the effect of the sociocultural aspects on the development and diffusion of Quantum computer technology is as yet hard to assess. The 'Essay Exploration Quantum Technology' (2019) provides an agenda for the debate in which sociocultural and societal effects are included.

13. **Accidents and unexpected events**
As with Quantum communication, there is little or no information available about accidents with Quantum computers. It is a fact that accidents are potentially possible: terrorists or rogue regimes can access classified data with Quantum computers. In addition, as a result of the noise in Quantum-bits, Quantum computers are not yet error-free, which can also lead to accidents.

[31] https://en.wikipedia.org/wiki/Quantum_computing
[32] https://thequantumdaily.com/2020/03/06/now-hiring-the-quantum-hr-challenge/

stt.nl