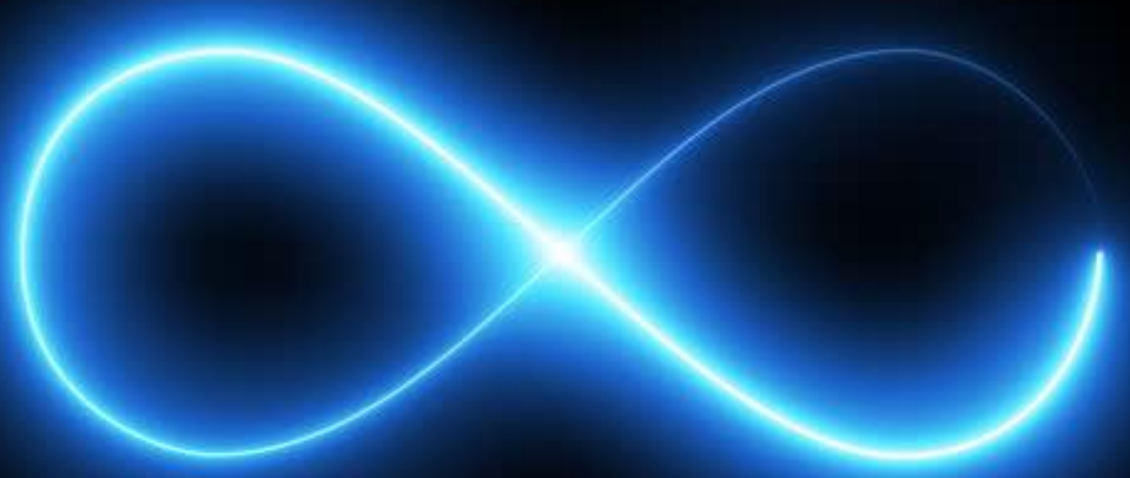
Lisa de Kluijver

Integration and Collaboration in the Development of Quantum Technology



Development of the Physical Layer of a Quantum Network Stack integrated with the Link Layer

A Vision on University-Industry Collaborations in the Field of Quantum Technology Development

TU Delft

June 2022

Integration and Collaboration in the Development of Quantum Technology

Development of the Physical Layer of a Quantum Network Stack integrated with the Link Layer

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By

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Summary

The traditional computer that we all use today has had a significant impact on the world we live in. Despite the fact that it was originally designed for doing calculations only, we now also use it to store information, retrieve data and process information. The use of the internet has become an integral part of our daily life. The quantum computer and the quantum internet, which connects these computers, are currently undergoing the same transformation. In parallel, other quantum technologies are also beginning to be developed. Some first-generation applications are already available on a small scale, but for most technologies important steps are still needed before 'quantum advantage' can be achieved. The technological and scientific challenges are numerous. Many years of research and development are still needed before the potential of quantum technology can be fully exploited.

The quantum computer is being developed in order to do more complex calculations and the quantum internet to communicate more securely. The properties of quantum bits, such as their ability to be in superposition and be entangled, are used to develop the quantum internet.

The quantum internet uses a network stack, consisting of different layers. Each layer has its own specific task to fulfil in order to make an application work correctly. The higher layer can use the services of the layer below, without having knowledge of the implementation details. The link layer is the lowest software layer of the stack, and is connected to the physical layer (the lowest layer of all), which contains the quantum bits and the hardware to control them.

In this thesis, the quantum bits are Nitrogen Vacancy (NV) centres in diamond. Microwaves can control the electron spin of the NV centre, which can be read out optically. Prior study has proven that two NV centres can become entangled in a heralding process. The real-time generation of entanglement between two NV centres, utilizing an abstraction layer in the form of the link layer, is innovative in the development of the quantum computer.

First, the control electronics are upgraded to manipulate the NV centre in real-time. The microcontroller unit (MCU) that manages the hardware to control and read the NV is now also in charge of communication with the link layer. To add this communication to the process, a new protocol is implemented in the MCU, consisting of multiple state machines. Each of the state machines is programmed to perform a specific hardware task before being ready for the next task. The operation of these state machines is proved and the communication with the link layer.

The fundamental job of the physical layer of the quantum network stack is delivering long-distance entangled state between neighbouring nodes. To test this capability, three quantum network tasks are performed. The first task is full state tomography of the delivered states. The density matrix of the entangled state is reconstructed and determined that the fidelity of this state is $F = 0.783(7)$. Secondly, the real-time selection of fidelity and the relationship between fidelity and latency are shown. The link layer requests entangled states with different fidelities, and the setup is able to provide the requested fidelities of the link layer in real-time. Moreover, it is shown that higher fidelity of the entangled state comes at the cost of higher latency. This means that it takes longer to produce this entangled state. The final task is showing remote state preparation of a qubit on a server by the client. Here, an entangled state is generated, after which the client prepares a state on the server by measuring its share of the entangled state. This remotely prepared state has an average fidelity of $F = 0.829(21)$. The successful execution of the tasks results in the demonstration of entanglement delivery using a quantum network stack.

Finally, a number of ideas for improvement are presented. These include expanding rotational gate possibilities, reducing waiting times, and gaining control over memory qubits. These improvements are needed for more complicated quantum network stack applications, such as Blind Quantum Computation.

Much R&D in the field of quantum technology is now done at universities. They have the most knowledge about the theories and try to make them into technologies that can be used in practice. The development of quantum technologies is relatively new, and much remains to be discovered. Although there is a lot of uncertainty about what the future with quantum will look like, there are also some possible applications of quantum that have already been thought and worked on.

Universities cannot do this development alone. They need funding from both the national government and the EU for research, but they also need to form collaborations with industrial partners to create applications of quantum technologies that can be used in practice. These industrial partners now often lack knowledge and expertise about quantum technology, but they do have financial resources to start collaborations for the development of new technologies.

For universities, the main purpose of these collaborations is therefore to commercialize their research ideas and test their potential in society. On the other hand, through these collaborations, they also want to create new knowledge faster and shift to a knowledge-based economy. This knowledge is also important for industry in order to gain a competitive advantage. Partnerships with universities also give them access to advanced research knowledge and infrastructures to grow their business.

Since both parties want to benefit from the collaboration, it needs to be determined how they will work together. The most potential lies in starting joint R&D projects to develop proof of concepts of the new technologies that can be used in the industry.

Some factors have a positive influence on the creation of these collaborations, such as making the transition from research laboratory to prototypes, obtaining funding, realizing economic impact, learning about the potential of new technologies or gaining PR value. Examples of factors that have a negative impact are scientific integrity, influence on research results, intellectual property rights, reluctance to invest in something uncertain, expectation management and the time and effort required to build relationships.

To create these partnerships, universities must take the lead. When industry is aware of the existence of quantum technology, knowledge transfer activities between universities and industry should teach them more about quantum and what quantum can do for their industry. This knowledge brings companies to a level of quantum acceptance. The drivers for collaboration compel companies to enter into collaborations with universities, but there are some barriers that must be overcome first. Some of these barriers are preconditions that must be met before further consideration can be given to entering into a collaboration. These include having the willingness to invest, having someone interested in the company, but also the university must be open to cooperation. When these conditions are met, the university and the company must make agreements about scientific integrity, intellectual property rights, influence of financiers and expectations. Only when these agreements are in place can joint R&D collaborations be successfully launched.

Acknowledgement

With the submission of this thesis, I have completed both part of my ambitious goal of doing two masters at the same time. The time I spent as a student on physics has therefore come to an end. I would like to express my gratitude to a number of people who have helped me throughout the thesis project.

First of all, I would like to thank my daily supervisor for applied physics, Matteo. Taking part in a project, which took you 3 years to figure out how it works, sometimes made it difficult to have even the slightest idea of what was going on. But your patience in explaining everything over and over again, your guidance in the lab and your enthusiasm got me through. I really enjoyed working on the project together, debugging the code we wrote ourselves, and getting a "fack yes" from you when something finally worked.
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I would also like to thank Eva for all the guidance she gave me during my communication project. All the discussions we had about what to call the result of my project; is it a framework, checklist, strategy, or maybe a vision. The feedback and support you gave me during the project helped me to get through it, and I am happy with the result. Also, Steven, in the beginning my motivation was not the highest, but through our conversations I learned more about myself and why I really wanted to finish this project with a good result. Thank you for that.

Finally, I would like to thank my family and friends for their support throughout the process. All the kind words when I was fed up, the supportive cups of tea during 'coffee' breaks and the questioning expressions on your faces when you asked me to explain quantum mechanics to you, helped me through.

Lisa de Kluijver
Delft, June 2022

List of Abbreviations

AOM Acousto-optic modulator.

APD Avalanche photodiode.

AWG Arbitrary waveform generator.

BQC Blind quantum computation.

CR check Charge and Resonance check.

DIO Digital input/output.

DM Dichroic mirror.

LAN Local area network.

MCU Micro Controller Unit.

MW Microwave.

NV Nitrogen-Vacancy.

PC Personal computer.

PSB Phonon-side band.

RF Radio frequency.

RO Readout.

RSP Remote state preparation.

SIL Solid immersion lens.

SP Spin pumping.

SPI Serial peripheral interface.

TCP/IP Transmission Control Protocol / Internet Protocol.

ZPL Zero-phonon line.

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Part I

General Introduction

Chapter 1

Introduction

1.1 Quantum background

In the 1980s, quantum computers were proposed. The idea for quantum computing came from what was once considered one of physics' greatest embarrassments: amazing scientific progress met with an inability to simulate even simple systems. Between 1900 and 1925, quantum mechanics was discovered, and it remains the foundation for chemistry, condensed matter physics, and innovations ranging from computer chips to LED lights. Despite these achievements, even the most basic quantum systems appeared to be outside the human capacity to model. This is due to the fact that simulating systems with even a handful of interacting particles necessitates far more computational power than any typical computer can give in millions of years!

With the theoretical proof that it must be possible to use quantum mechanics in a computer to generate much more computing power, the first physicists set to work trying to build one. This is not as easy as it sounds, because quantum mechanical properties only apply to very small particles, and often have a short lifespan. Therefore, in order to see the working principle of quantum mechanical properties, systems must first be developed that make these properties visible. Only then can these properties be worked on, to eventually turn them into a quantum computer.

At the time of writing, the technologies are still nowhere near a truly working quantum computer with more computing power than a classical computer. But the first steps have been taken in researching the best type of quantum bit on which to build the computer. Several research groups around the world are working on different types of quantum bits to find the most suitable one.

Apart from the work on quantum computers, there is other work being done in the field of quantum technologies. Developments are also being made in quantum communication systems, quantum sensors and quantum simulators. On a small scale, some first generation applications are already available, but for most technologies important steps are still needed before 'quantum advantage' can be achieved. The technological and scientific challenges are numerous. Many years of research and development are needed before the potential of quantum technology can be fully exploited.

1.2 Quantum hype

The promise of the advent of quantum computers and other quantum technologies is making an enormous amount of money available for research into these technologies. Every company and government that has the money and understands the benefits of quantum technologies wants to invest now, to be at the forefront of this field and reap the first benefits when quantum technologies become practical.

This is called quantum hype. What a researcher needs to do to get funding for their work is to exude enthusiasm about the fact that quantum technologies will have groundbreaking, world-changing applications, and that they will soon be available. These promises that are made about quantum technologies may be true on paper, but in reality, the speed of these developments and what can ultimately be done with them is a point of contention for critics. They say that a huge hype is being created about quantum, and we will have to wait and see what eventually becomes reality.

1.3 Quantum networks

One of the promises of quantum technologies is secure communication via a quantum internet or quantum network. Compared to the 'classical' computer, the quantum computer is developed to be able to perform more complex calculations and the quantum internet to be able to communicate more securely. With 'classic' internet connections, information is sent encrypted to protect it from people who want to do harm. The internet ensures that you can send an e-mail or make an online payment safely.

To do this on your 'classic' computer, you do not need to know what is going on in your computer's software and hardware. You just need to know how to write an email in the online application and press send, the computer, or rather, the internet does the rest for you.

The fact that you can send email over the internet is possible because your computer's software and hardware work well together. For quantum computers, the hardware will be different and therefore, the 'classic' computer software will no longer work on the quantum hardware. New software must be developed for the quantum computer. This software must then be linked to the quantum hardware, to make the quantum internet work.

In research for the Applied Physics master's degree, I worked on the development of the physical layer of the quantum network stack, as part of the quantum internet protocol. In this stack it is the hardware layer that must be linked to the software. The software is not one large block of code, but consists of multiple layers, each with its own task. We have linked the hardware layer to the lowest software layer, as a starting point for the further development of the quantum internet.

1.4 Collaboration on quantum technologies

Since most quantum technologies still require significant steps before quantum advantage can be achieved, a lot of research needs to be done. This research usually takes place within universities, as it is mostly fundamental work to figure out how to turn theories into practical applications.

A lot of money is allocated to this research, because of the high promises that quantum technologies hold. Several parties benefit from accelerating the development of quantum technologies. The aim of the research is to eventually create practical applications for quantum technologies. Industry should be able to use and benefit from these applications.

To get the applications into industry, it is now important to establish collaborations between universities and industry. In these collaborations, the emphasis should be on getting the technology working, getting it out of the laboratory and into practice. In effect, commercializing the technologies to make an economic impact.

Exactly what these collaborations should look like is still unclear. Therefore, the research in this thesis will first focus on getting a clear picture of whom the stakeholders are. With the known stakeholders, the purpose of the collaboration can be determined. What is the purpose of the collaboration and when that is clear, how should the collaboration take place. So what is the type of collaboration that is needed. In addition, it can be determined which factors influence the collaboration, both positively and negatively.

If all these aspects are known, a detailed picture of university-industry collaboration in the field of quantum technology development emerges. This can be used to create a vision for these collaborations in the future, as a starting point for establishing new collaborations to create more applications of quantum technologies in industry more quickly.

1.5 Thesis structure

This is a combined thesis for the masters Applied Physics and Communication Design for Innovation at TU Delft. The Applied Physics part focuses on quantum networks, in particular on the development of the physical layer of a quantum network stack integrated with the first software layer, the link layer. The communication part focuses on the collaboration between universities and industry in the development of applicable quantum technologies. The structure of the thesis is visualized in figure 1.1. This chapter is the general introduction to the research topic, quantum technologies, and the two studies that follow for each master.

The second part of the thesis outlines the research done for Applied Physics. It first starts with the technical background about quantum mechanics and the use of quantum bits. Then the background of quantum network stacks and communication between the two layers is investigated. With this information, the physical layer is developed and linked to the first software layer. The results and discussion are also presented in this second part.

The third part examines the collaboration between universities and industry in the development of quantum technology. It starts by examining the stakeholders, the purpose, and the type of collaboration. These collaborations are influenced by positive and negative factors, which will be outlined. With these results, a vision is developed for what these university-industry collaborations should look like. This result and the discussion of this vision will also be presented in this part of the thesis.

In the final part, an overall conclusion and outlook on the future of quantum technologies will be outlined. This will be based on the findings, both from the physics part and the communication part.

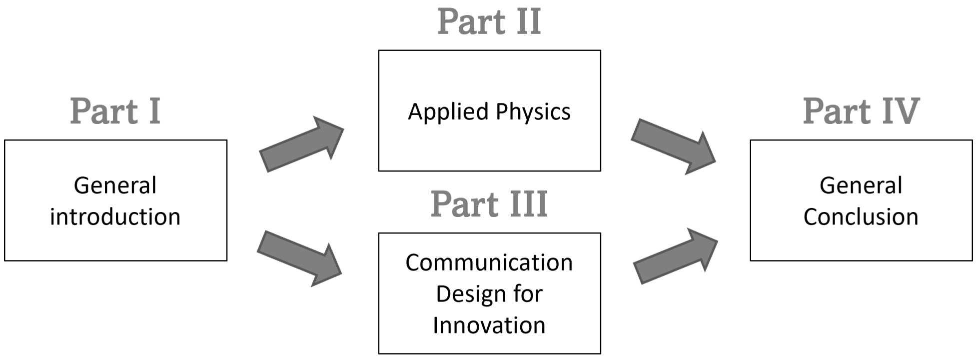


Figure 1.1: ***Thesis structure.*** *First, a general introduction to the subject is given. The second part contains the research done for the Master of Applied Physics. The work done for Communication Design for Innovation is presented in the third part. The fourth and final section presents the general conclusion of the two works together.*

Part II

Applied Physics

Chapter 2

Introduction

Quantum mechanics is one of the most reliable and effective structures for describing the world we live in. With its weird behaviour and counter-intuitive implications, it has perplexed those who research it. Quantum mechanics has two concepts that cannot be found anywhere else in the classical world. These are entanglement and superposition.

The idea behind superposition is that a quantum bit (qubit), the counterpart of the classical bit in a computer, can not only be 0 or 1, but also a combination of both at the same time. The qubit will hold its superposition state until it is measured. When the qubit is measured, it will fall back in to the classical states 0 or 1. Next to superposition, qubits have the ability to entangle to another qubit. Entanglement is a phenomenon in which the state of one particle links inextricably to the state of another particle. That means that if one measures and knows the state of the first particle, the state of the second particle is also known without measuring it. The entanglement principle even holds when the two entangled particles are far away. These two concepts can be used in quantum computation and communication.

A classical computer is not just an assembly of a lot of classical bits, but it is much more complex. It consists of a collection of software and hardware parts that are connected to each other, forming a network stack. A stack consist of multiple layers that are connected to each other, all having a specific task to fulfil in order to make an application performed by the user work correctly. The classical bits are part of the hardware layer of the stack. The stack used for the classical computer can not be copied identically to a quantum computer, because the quantum computer works on quantum bits and entanglement. Dahlberg et al. [1] proposed a network stack for quantum devices, in which the quantum bits and entanglement between them are part of the hardware layer.

The generation of entanglement between two remote quantum nodes has already been demonstrated on several platforms, including the Nitrogen Vacancy (NV) centres [2, 3, 4]. NV centres can be controlled and measured with high fidelity in the lab [5]. Therefore, they can be used as nodes of a quantum network.

Although a lot of research has already been done, the world is still far away to having a quantum computer. Research has recently established a three-node quantum network of NV centres connected by entanglement [5]. In this case the entangled link could be used for quantum computation, a big step forward, hopefully leading to a real quantum computer. One of the next fields of research that should be pursued is connecting more nodes in the lab. On the other hand, to abstract functionality and make the network more modular, it is necessary to control these nodes from outside the lab. This makes it possible for the system to grow in capabilities without exploding in complexity. Physics experiments on a two-node quantum network are going to be integrated with higher levels of abstraction in the control, so that users without knowledge of the underlying hardware can use the system to, e.g., perform entanglement generation or teleportation [6]. Therefore, this research will focus on making a platform-agnostic connection between the hardware side (physical entanglement) and software-side to form the next step towards a real-world quantum network.

This real-world quantum network, or quantum internet, offers many opportunities that are provably impossible by using only classical information. It is impossible to predict all the potential quantum Internet's applications, as it is with any radically new technology. Several major applications, however, have already been identified. Wehner et al. [7] described the following applications for a quantum internet: secure communication, clock synchronization, extending the baseline of telescopes, secure identification, achieving efficient agreement on distributed data, exponential savings in communication, quantum sensor networks, as well as secure access to remote quantum computers in the cloud.

The focus of this thesis is on developing the physical layer of a quantum network stack and show the integration with the link layer, the first software layer of the quantum network stack. In chapter 2 the theory on NV centres in diamond is laid out. Those NV centres are the quantum network nodes used in the physical layer in the experiments. Besides, this chapter contains theory on how to control the NV centres, including all hardware necessary. In chapter 3 the methods used to build the connection between the physical and link layer is stated. This consist of theory on the quantum network stack, the communication interface between the layers, a description of the handling of the communication on the physical layer side and a demonstration of the connection between the layers. In chapter 4 the three quantum network tasks to evaluate the implementation of the link layer – full state quantum tomography, real-time selection of fidelity and remote state preparation – are defined. In chapter 5 the results of these tasks are shown, including a discussion on their meaning. Chapter 6 contains the conclusion on the performance of the physical layer of the quantum network stack and the integration with the link layer. Based on the results, an outlook for further research is given.

Chapter 3

Theory

3.1 Nitrogen-Vacancy centre in diamond

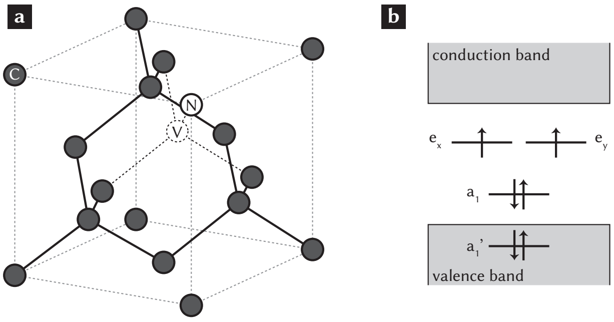


Figure 3.1: ***The basic structure of the NV centre in diamond. a)*** *A substitutional nitrogen atom (N) next to a lattice vacancy (V) forms the nitrogen-vacancy centre in diamond's carbon lattice.* ***b)*** *Molecular orbitals and their filling in the NV$^-$ orbital ground state (labels denote symmetry). Adapted from Bernien, Pfaff [8, 9].*

The carbon lattice of diamond can have different optically active defects which can be used as qubits. I focus only on the Nitrogen-Vacancy (NV) centre in this thesis. The NV consists of a nitrogen atom and an adjacent vacant lattice site, see figure 3.1a. In its neutral charge state, NV^0, there are 5 electrons present. Two of them come from the nitrogen atom, and the other three are the unpaired electrons from the carbon atoms around the vacancy. The negative charge state NV$^-$ has drawn more interest because of its favourable quantum properties. In this state, another electron is captured from the environment.

The electronic wave function can be approximated by a linear combination of the available atomic orbitals around the vacancy. These consist of the dangling sp^3 orbitals of the vacancy-neighbouring atoms (carbon and nitrogen). In figure 3.1b the electronic occupations of the six electrons in the molecular orbitals in the ground state is shown. All energy levels lay within the band gap of diamond. The result is that the NV$^-$ has optical properties similar to those of an individual trapped ion.

The six electrons in the system interact with each other via spin-spin interaction, spin-orbit interaction and Coulomb repulsion. This makes them form an orbital-singlet spin-triplet ground state that optically couples to an orbital-doublet spin-triplet excited state, as can be seen in figure 3.2. Besides, spin-singlet states exist, through which the excited state can decay. Decaying from the spin-singlet state to the spin-triplet ground state favours the $m_S = 0$ spin projection [10].

The difference between the zero-phonon line (ZPL) and the phonon-side band (PSB) is shown in figure 3.2. By decaying from the excited state to the ground state, the NV can emit photons through the ZPL or PSB. When the wavelength of the emitted photon exactly matches the energy difference between the excited state and the ground state, the photon is emitted in the ZPL. In the decay process it can also happen that not only a photon, but also a phonon, is released. This photon and phonon must share the energy corresponding to the energy difference between the excited state and the ground state. This means that the wavelength of the photon changes with respect to the wavelength of the photon emitted in the ZPL.

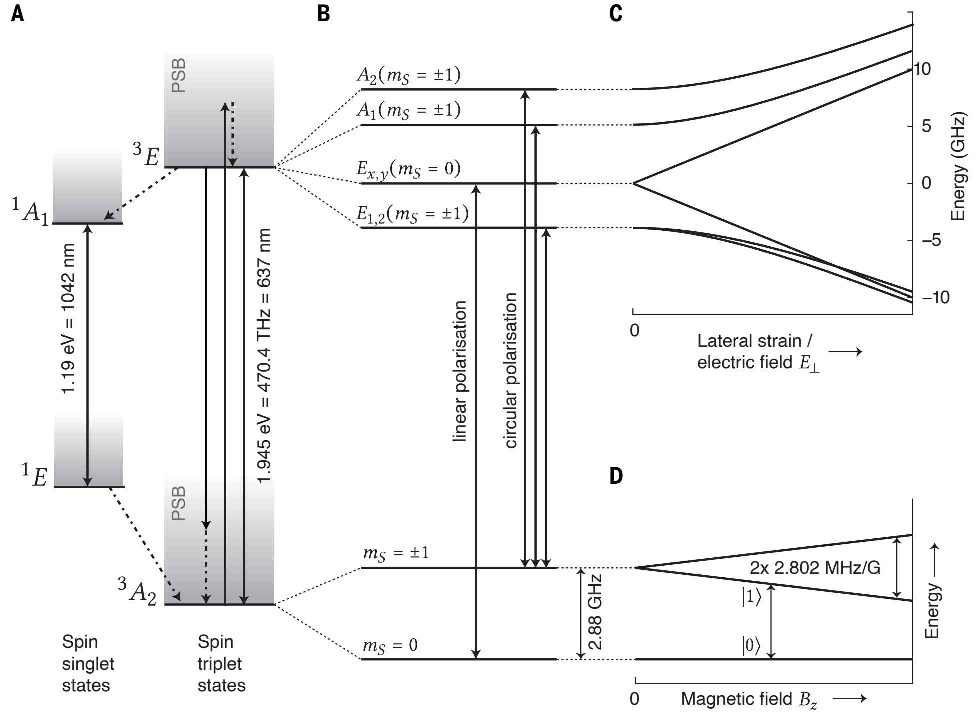


Figure 3.2: ***The electronic structure of the NV$^-$.*** ***a)*** *The excitation of the NV from the ground state $^3A_2$ can happen resonantly or off resonantly via the phonon-sideband (PSB). The relaxation can happen similarly by emitting photons resonantly through the zero phonon line (ZPL), or off-resonantly via the PSB or the singlet states.* ***b)*** *The ground level of the NV has a zero field splitting that separates the $m_S = 0$ state and the two degenerate states $m_S = \pm 1$. Spin-spin and spin-orbital interactions split the excited state into six energy levels, which can only be resolved at cryogenic temperatures. There are two levels ($E_{x,y}$) that correspond to $m_S = 0$ and four levels that correspond to $m_S = \pm 1$ ($E_{1,2}$, $A_{1,2}$).* ***c)*** *The levels of the different excited states are split by lateral strain or electric field. It is feasible to tune the frequency of optical transitions to several GHz by applying an electric field, which is essential for photon indistinguishability during entanglement generation.* ***d)*** *The $m_S = \pm 1$ level splits by the Zeeman splitting and allows the definition of a qubit within the ground state triplet. Adapted from Bernien, Pfaff, Hensen [8, 9, 11].*

3.1.1 Hamiltonian

The orbital ground state ($S = 1$) can have spin projection $m_S = 0$ and $m_S = \pm 1$. They are separated by $D \approx 2.88$ GHz, due to spin-spin interactions. By applying an external magnetic field, the $m_S = \pm 1$ states are split via the Zeeman effect with an electron gyromagnetic ratio of $\gamma_e \approx 2.802$MHz/G seen in figure 3.2d. When neglecting the electric field, $\boldsymbol{E}$, and lateral strain, the Hamiltonian of the electron spin ground state can be described as:

$$H_e = DS_z^2 + \gamma_e(S_xB_x + S_yB_y + S_zB_z) \tag{3.1}$$

with the spin-1-matrices S_i. The ground-state spin state can be used as the qubit: $|0\rangle \equiv m_S = 0$ and $|1\rangle \equiv m_S = \pm 1$. Because of the better performance (gate and measurement fidelities) of the $m_S = +1$

spin state, it is used as the $|1\rangle$ within the experiments of this report and the m_S = -1 spin state is not used.

Besides the electron spin of the NV centre, the ^{14}N nuclear spin and its interaction with the electron spin have a contribution to the total Hamiltonian of the system. These contributions can be described as:

$$H_N = -Q_N I_{N,z}^2 \tag{3.2}$$

where $Q_N = 4.98$ MHz is the quadrupole splitting — which separates the nitrogen-spin states $m_I = 0$ and $m_I = \pm 1$ with no magnetic field applied — and

$$H_{eN} = \gamma_n (I_x B_x + I_y B_y + I_z B_z) + \boldsymbol{S} \cdot \boldsymbol{A_N} \cdot \boldsymbol{I_N} \tag{3.3}$$

where the nitrogen-spin gyromagnetic ratio $\gamma_N = 0.3077$ kHz/G, $\boldsymbol{I_N}$ are the spin-1 operators for ^{14}N and the hyperfine tensor $\boldsymbol{A_N}$ describing the electron-nitrogen interaction.

In the neighbourhood of the NV centre, multiple ^{13}C spins are present. They will also influence the Hamiltonian of the system, but their contribution is too low to be taken into account for the scope of this thesis. These ^{13}C spins in the environment can not be completely ignored, they need to be taken into account while doing dynamical decoupling to preserve the quantum state, explained in 3.2.3.

3.2 Devices to control and manipulate the NV centre in diamond

To control the NV centres in diamond, the experimental setup consists of multiple elements. These include electronics which control and communicate with the other components of the setup, optical elements to do the initialization and read-out of the electron spin, microwave (MW) and radio-frequency (RF) signals to manipulate the state of electron (and nuclear spins), a magnetic field to make controllable energy level splitting due to the Zeeman effect and cryogenics to create an environment of 4K for the diamond. This low temperature is needed to do proper read out of the state of the electron spin and make spin-photon entanglement. Both actions require a spin-selective excitation from the ground state to the excited state. At temperatures above 4K the hyper fine structure of the excited states (see figure 3.2b) gets lost. All these elements need to work together in order to perform experiments on a single NV centre. The layout of this setup is shown in figure 3.3.

3.2.1 Diamond devices

The single NV centres used in the experiments occur naturally in chemical-vapour-deposition ultrapure type IIa diamonds, which have no measurable nitrogen impurities and are colourless [12]. Those diamonds have a natural abundance of 1.1%^{13}C atoms and are grown in the $\langle 100\rangle$ crystal orientation. After they are grown, they are cut along the $\langle 111\rangle$ crystal direction.

The NV centre is located within the diamond lattice. It is ensured that the NV centre does not couple to other NV centres and isn't located directly next to an ^{13}C atom. Both another nitrogen atom and an ^{13}C atom make it more difficult to control the electronic spin of the NV centre.

To improve the collection efficiency of photons from the NV centre, a hemispherical Solid Immersion Lens (SIL) is positioned around the NV centre, see figure 3.4. The photons coming from the centre have a normal angle of incidence with respect to the surface. In that way, no refraction or total internal reflection occurs. The SIL is made by milling away diamond with a focused ion beam. To improve further the photon collection efficiencies and enhance the signal-to-noise ratio when exiting with 637nm light, an anti-reflective coating of Al_2O_3 is grown — via atomic layer deposition — on top of the SIL.

A gold stripline is applied to the diamond's surface to deliver radio and microwave signals to the NV to control the electron spin. Furthermore, for DC Stark-tuning of the excited states, gold electrodes are made. Tuning is required for producing indistinguishable photons between two NV's for remote entanglement generation.

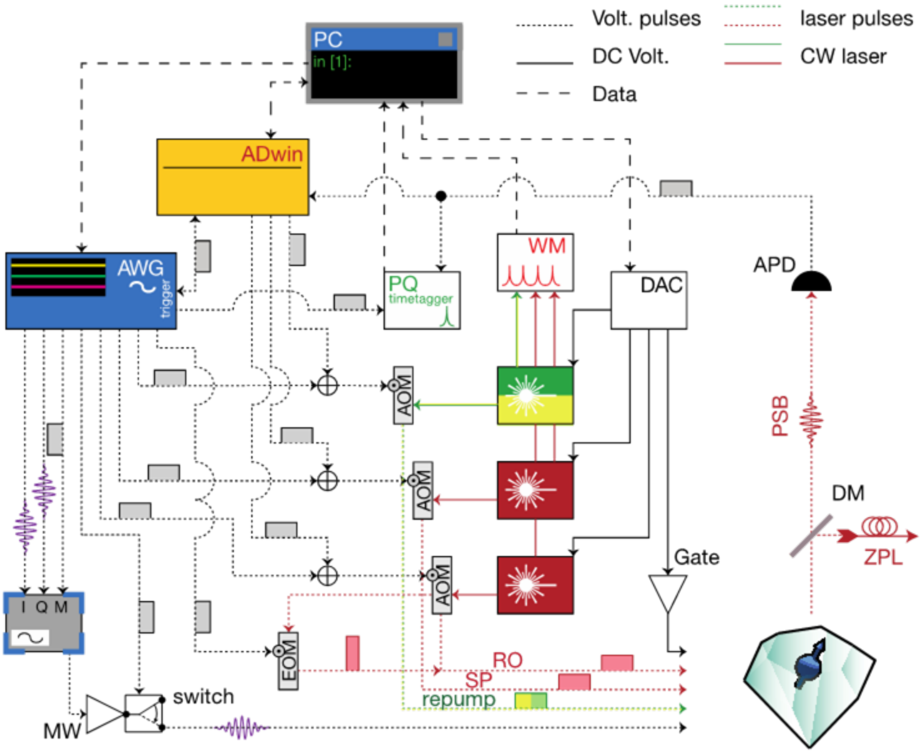


Figure 3.3: ***Setup for NV control.*** *The PC programs the control loop on a microcontroller (ADwin) and the pulse sequences on an arbitrary waveform generator (AWG; Zurich Instruments HDAWG8). The AWG is triggered by the ADwin to start pulse sequences, and the AWG notifies the ADwin when sequences are completed. There are more digital channels that allow more complex communication between AWG and ADwin. The laser pulses for charge re-pumping, electron spin pumping (SP), and electron spin readout (RO) are made by acoustic-optic modulations (AOM) controlled via both the AWG and ADwin. The read-out light (RO) can also be controlled by an electric-optic modulation (EOM), which is controlled by the AWG. The laser frequencies are measured by a wavemeter (WM, Highfinnesse WS6) and controlled by the ADwin. The AWG sends modulated I and Q pulses as well as a trigger signal (M) (Rhode and Schwarz SGS100) to an MW source. The output signal of the MW source is amplified (Amplifier Research 40S1G4 or Amplifier Research 25S1G4A) and sent via an AWG-controlled MW switch. The light from the NV is spectrally split into a zero-phonon line (ZPL) and a phonon sideband (PSB) via a dichroic mirror (DM). An avalanche photodiode (APD) detects photons from the PSB, and the counts are recorded by the ADwin for counting and by a time-to-digital converter (PQ, PicoQuant TimeHarp 260N or Hydraharp 400) synchronized with the AWG for time-resolved measurements. Adapted from Bernien, Pfaff [8, 9].*

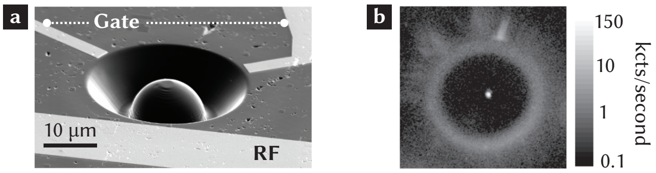


Figure 3.4: ***Solid Immersion Lenses.*** ***a)*** *To improve collection efficiency, the NV is located in the middle of a hemispherical solid immersion lens (SIL). The microwave (MW) and radio frequency (RF) signals are sent to the NV via a gold strip line.* ***b)*** *Green laser excitation of a confocal scan. The NV can be localized as the bright spot in the centre of the SIL. Adapted from Bernien, Pfaff [8, 9].*

3.2.2 Optical addressing

In the experimental setup, optical elements are used to check the charge and resonance of the NV centre, initialize the NV and do a read-out on the state of the NV. The control and working principles of these elements are described here.

Charge and Resonance verification

In order to be able to use the NV centre as a qubit, it should have the right charge state and be on the correct resonance frequencies. There are two main hurdles to overcome to get the charge and resonance state of the NV correct. The first one has to do with the charge state: NV^- can fall back into the NV^0 state. NV^- can be ionized under optical illumination via a two-photon absorption process [13]. The second hurdle appears when the NV centre changes resonance frequencies due to local charge changes in the environment. These modify the optical transition frequencies of the NV, which means that the excited state energy levels move in the range of hundreds of MHz [14]. This results in different wavelengths needed to excite the ground state, but more importantly, changes the wavelength of the emitted photon. Entanglement between two qubits is generated through the emitted photons of the two separate NV centres, which should therefore be indistinguishable. A fluctuating wavelength lowers the rate at which entanglement is generated. The need to actively stabilize the emission frequency reduces the entanglement rates by approximately a factor of two [5].

To get the NV centre in the NV^- state and on the right resonance frequencies, it should be excited with a laser tuned to the expected resonance frequencies. In an attempt to bring the NV centre to resonance, the photons in the PSB are counted while resonantly exciting the NV centre. When the amount of counted photons is below a certain threshold, a new attempt is done to get the NV on resonance.

There are two possible laser options to get the NV centre in the NV^- state. One laser that can be used is a green laser — $\lambda \approx 532$nm — with high intensity (tens of μW) and short (tens of μs) pulses. The green laser pulses are not only charging the NV centre but also the environment of it. This may cause a change in the charge environment of the qubit, which is not desirable. The main advantage of using the green laser is that it is quick, and you don't need to find the right frequency, it's an off-resonant process.

The second option is using a yellow laser instead of green laser light. The yellow laser — $\lambda \approx 575$nm — has weak (tens of nW) and long (hundreds of μs) pulses. These pulses are exciting the Zero-Phonon-Line (at 575nm) of NV^0, to excite one of the 5 electrons present to make space in the ground state for the sixth electron. To be able to do this, the laser has to be on resonance with the NV, just like you have to be on resonance for the readout laser and spin-pump laser (both explained in next pages).

Initialization

To initialize the NV centre, laser light is used to pump the electron into the $m_S = 0$ state. The two $m_S = |1|$ ground states are coupled to the optical excited states $E_{1,2}$. Since these optical excited states have a poor cyclicity, they make it possible to rapidly pump the spin-state into $m_S = 0$ state with high fidelity ($>$0.99) [5]. In this way, the spin selective optical interface of NV^- can be used to initialize the qubit with high fidelity, which is needed for the rest of the experiment. This process is called Spin-Pumping (SP) and is executed by the SP-laser.

Optical Read-Out

To determine the state of the qubit, an electron spin Read-Out (RO) should be done. The state of the qubit can be any state on the Bloch Sphere, but when reading out, the state projects on $|0\rangle$ or $|1\rangle$. For example, if the state is in a superposition of $\alpha |0\rangle + \beta |1\rangle$ (with α, β between 0 and 1, and $\alpha + \beta = 1$) and a measurement is made, the result will be either 0 or 1.

The state of the qubit obtained by shining the read-out laser, which is only resonant with the $|0\rangle$ state, the qubit gets into the excited state $E_{x,y}$ and falls back into the $m_S = 0$ ground state. By collecting emitted photons coming from the NV, the state can be determined. If one or more photons are detected, it assured the spin-state was in the bright $m_S = 0$ ground state. When no photons are detected at all — the system stays dark —, the spin-state was $m_S = \pm 1$. In order to be sufficient for the read out of the spin state, a protocol where only the $m_S = 0$ and $m_S = -1$ are populated needs to be executed.

The read-out fidelity of the $m_S = \pm 1$ spin state is limited by the off-resonant excitations of the $m_S = 0$ ground state and the detector dark counts. The ZPL-photon detectors sometimes give the signal a photon is collected, while there were no photons coming from the NV centre. These are called dark counts and are unavoidable. The lower the dark count rate, the less the fidelity is affected.

There is a chance a photon is emitted by the NV, because it is in the $m_S = 0$ spin state, but gets lost on its way to the ZPL-photon detector. The detector will not detect any photon and the state is wrongly indicated as the $m_S = -1$ spin state. The finite collection efficiency and the spin-flip probability per optical cycle to the $m_S = \pm 1$ state and are limiting the read-out fidelity of the $m_S = 0$ spin state.

3.2.3 Electron spin control

The electron spin in the ground state can be controlled via MW pulses. These pulses are sent to the NV centre via the strip line on the diamond, see figure 3.4. The MW signal generates an oscillating magnetic field that controls the state of the spin. The frequency of the pulses is on resonance with the qubit transition between $m_S = 0$ and $m_S = -1$ ground states. By calibrating the pulse duration and amplitude of the microwave pulse, specific rotating angles such as $\pi/2$ and π can be executed.

The surrounding nuclear spins are interacting with the electron spin via the magnetic hyperfine interaction. The isotopes ^{13}C in the environment form a nuclear spin bath that induces a fluctuating magnetic field around the NV centre. This fluctuating magnetic field affects the fidelity of the superposition of the NV spin states, as it will decohere NV. The coherence time (T_2) of the NV can be extended by performing dynamic decoupling.

Dynamical decoupling

Dynamical decoupling is applying regularly-spaced microwave pulses to the NV [15]. In this thesis the dynamical decoupling used is the XY8 sequence, which consists of N pulse sequences of π pulses around, alternating between, the X and Y axis. Although the π pulses get calibrated, they are not perfect. Therefore, the alternation between the X and Y axes is needed to compensate for small errors in the performed pulses.

Figure 3.5 shows the NV superposition state's fidelity as a function of evolution time and a varying number of pulse sequences (N). The time in between two pulses is 2τ. Not every inter-pulse delay τ can be used, τ should be off-resonance with the ^{13}C atoms in the environment. In the points, not in the fits, small dips can be seen. Those dips in fidelity correspond to the NV coupling to ^{13}C spins further away in the environment. Having a higher N, meaning higher number of pulse sequences, extends the lifetime of the superposition state.

3.3 Entanglement between two NV's

The electronic spin states of two NV centres in different diamonds can be entangled with the use of photons (flying qubits). The electron spin state of each NV centre is entangled with the single photon the NV emits (after being brought to the excited state). A single photon protocol is used to create entanglement between the two NV centres. This is done by overlapping the photonic modes of the two NV centres on a beamsplitter. When one photon is detected at one of the output ports of the beamsplitter, the spins are projected on a symmetric joint state.

Figure 3.6 shows the setup of the single-photon protocol. Both NV centres are initialized in the same state. They are excited by a laser and have a chance to emit a photon. The photons are led to a beam splitter, in which they will arrive at exactly the same time. When a single photon is detected by one of the detectors after the beam splitter, it is unknown from which NV the photon originates. This ensures that the two NV centres are now entangled.

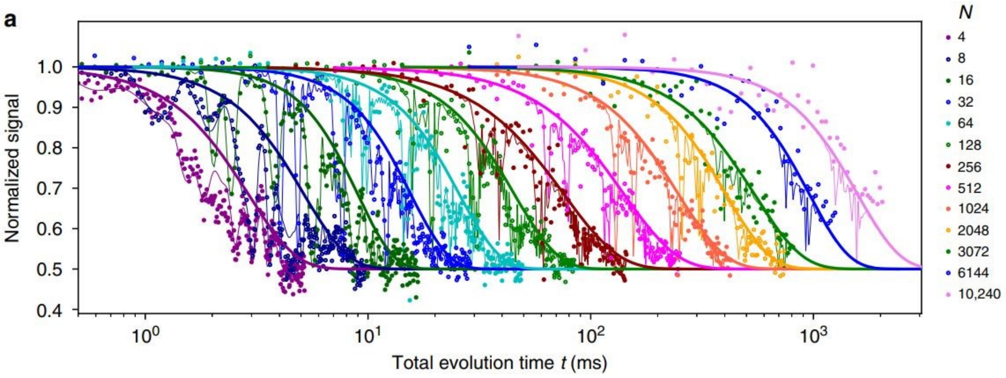


Figure 3.5: ***Decoupling sequence improves coherence time of quantum state.*** *While the NV is in superposition state, a total of N pulse sequences (varying from N = 4 to N = 10240) is applied to extend the coherence time. The decoupling sequence used is the XY8 scheme. The solid lines are fits for each specific N. Adapted from Abobeih [16].*

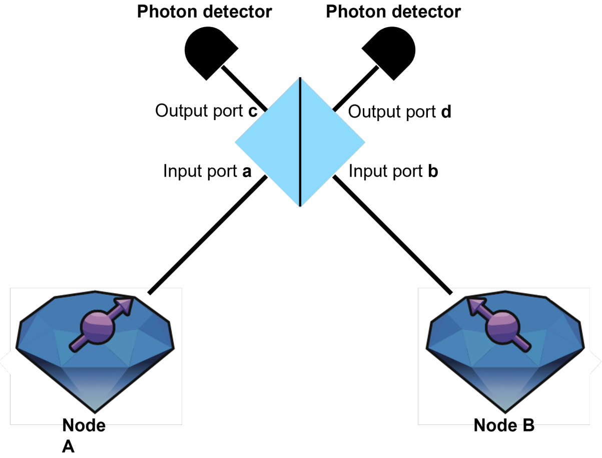


Figure 3.6: ***Single-photon protocol setup.*** *The possible emitted photons coming from the two NV centres are guided to input ports a and b of a shared beam splitter. After arriving at the same time at the beam splitter, they will leave via output port c or d and are observed by the photon detectors. It is uncertain from which NV a single photon originates when only one photon is detected by one of the detectors following the beam splitter. As a result, the two NV centres are entangled.*

A heralding entanglement protocol is used to generate entanglement. In this protocol, $|0\rangle_{ph}$ means absence and $|1\rangle_{ph}$ the presence of a photon. The NV qubit states, $m_S = 0$ and $m_S = \pm 1$, are relabelled such that $|\uparrow\rangle \equiv |0\rangle$ and $|\downarrow\rangle \equiv |1\rangle$.

First, both NV centres are initialized in a spin superposition state. Each initialized state looks like:

$$\sqrt{\alpha}\,|\uparrow\rangle + \sqrt{1-\alpha}\,|\downarrow\rangle \tag{3.4}$$

with α the bright state probability. $|\uparrow\rangle$ is called the bright state, since it will emit a photon during read-out.

Next, a spin-selective optical pulse excites the NV centre (only if in the $|\uparrow\rangle$ state) after which it decays by emitting a photon. The state of the total system becomes:

$$\begin{aligned}&(\sqrt{\alpha}\left|\uparrow\right\rangle_A \left|1\right\rangle_{ph,A} + \sqrt{1-\alpha}\left|\downarrow\right\rangle_A \left|0\right\rangle_{ph,A}) \otimes \\ &(\sqrt{\alpha}\left|\uparrow\right\rangle_B \left|1\right\rangle_{ph,B} + \sqrt{1-\alpha}\left|\downarrow\right\rangle_B \left|0\right\rangle_{ph,B}).\end{aligned} \tag{3.5}$$

The beamsplitter has the input ports *a, b* and output ports *c, d,* shown in figure 3.6. Sending the photons through the beamsplitter leads to:

$$\left|1\right\rangle_{ph,A,a} \rightarrow \frac{\left|1\right\rangle_{ph,A,c} + \left|1\right\rangle_{ph,A,d}}{\sqrt{2}}; \quad \left|1\right\rangle_{ph,B,b} \rightarrow \frac{\left|1\right\rangle_{ph,B,c} - \left|1\right\rangle_{ph,B,d}}{\sqrt{2}}. \tag{3.6}$$

Assuming that the photons are completely indistinguishable, i.e., $\left|1\right\rangle_{ph,A,(c,d)} = \left|1\right\rangle_{ph,B,(c,d)}$ and using the standard definitions for annihilation and creation operators $a_i\left|n\right\rangle_i = \sqrt{n}\left|n-1\right\rangle_i$; $a_i^\dagger\left|n\right\rangle_i = \sqrt{n+1}\left|n\right\rangle_i$, the total system ends up in this state:

$$\begin{aligned}&\frac{\alpha}{2}\left|\uparrow\right\rangle_A\left|\uparrow\right\rangle_B(\left|2\right\rangle_{ph,c}\left|0\right\rangle_{ph,d} - \left|0\right\rangle_{ph,c}\left|2\right\rangle_{ph,d}) \\ &+ \sqrt{(\alpha-\alpha^2)/2}(\left|\uparrow\right\rangle_A\left|\downarrow\right\rangle_B + \left|\downarrow\right\rangle_A\left|\uparrow\right\rangle_B)\left|1\right\rangle_{ph,c}\left|0\right\rangle_{ph,d} \\ &+ \sqrt{(\alpha-\alpha^2)/2}(\left|\uparrow\right\rangle_A\left|\downarrow\right\rangle_B - \left|\downarrow\right\rangle_A\left|\uparrow\right\rangle_B)\left|0\right\rangle_{ph,c}\left|1\right\rangle_{ph,d} \\ &+ (1-\alpha)\left|\downarrow\right\rangle_A\left|\downarrow\right\rangle_B\left|0\right\rangle_{ph,c}\left|0\right\rangle_{ph,d}.\end{aligned} \tag{3.7}$$

The detectors do not discriminate between the $\left|2\right\rangle_{ph}$ and $\left|1\right\rangle_{ph}$ states.

To be allowed to make the assumption the photons coming from both NV centres are indistinguishable, only photons emitted into the ZPL can be used. Only those photons are reliable, since the photons in the PSB have an additional phonon with them in the decay process. This phonon is also entangled to the electron spin of the NV centre. So, when this phonon is lost, the full entangled state is also lost. This makes photons coming from the PSB are unwanted in entanglement generation.

The drawback is the low percentage of photons emitted in the ZPL during the decay process. Only ∼3% of the photons are emitted into the ZPL, the rest ends up in the PSB. Besides, photons are lost due to imperfections in the collection optics. Due to the low number of photons in the ZPL, collection imperfections and the assumption of symmetric detection efficiencies, the probability for a two-photon-emission event in which only one photon is detected is given by the bright state probability α. To get a high state fidelity, α should be low. The entanglement success rate (r) depends also on this α and on the probability of detection (p_{det}) in the following way: $r = 2\alpha p_{det}$ [5]. So, by lowering, α the entanglement generation success rate drops. Therefore, varying α in the experiment a trade-off between entanglement generation success rate and the state fidelity that is realized.

Chapter 4

Methods

The generation of entanglement between two distant quantum nodes has already been demonstrated on various platforms, including the nitrogen vacancy (NV) centre [10, 11, 16]. The next step towards a quantum internet in the real world is to create a platform-agnostic connection between the hardware side (physical entanglement) and the software side. This connection is one of the connections within a network stack. The classical internet is built on the TCP/IP stack, but for the quantum computer a new network stack must be developed [17].

4.1 Network stack

Classical network devices contain a network stack, which is a collection of software and hardware parts connected to each other to run applications over a network. A stack consist of multiple layers that are connected to each other, all having a specific task to fulfil in order to make the application work correctly. The idea of the layers is that a higher layer can use the information (also called service) of the layer below, without having knowledge of the implementation details. This implementation of the lower layer is called a protocol. Often there is more than one protocol per layer, each for a different service the layer can provide. In order to execute a certain protocol, the higher layer must know via which interface it must communicate with the lower layer and which services are available at that lower layer. The main advantage of the layer system is the abstraction of technical details of each separate layer and developing protocol for higher layers independently of lower layers.

4.1.1 The classical internet protocol

The TCP/IP is the protocol used for internet on classical computer. TCP/IP is a stack that consists of five layers: the physical layer, the link layer, the internet layer, the transport layer and the application layer [18]. In the rest of the report, the focus is only the physical layer and link layer.

All the hardware, cables, etc are part of the physical layer. This layer is also responsible in the TCP/IP for transmitting bits from one computer to another. The link layer is responsible for sending messages between two nodes on the same network. All available nodes in the network are known in this layer, and messages are passed to one another based on the MAC-address (Media Access Control address).

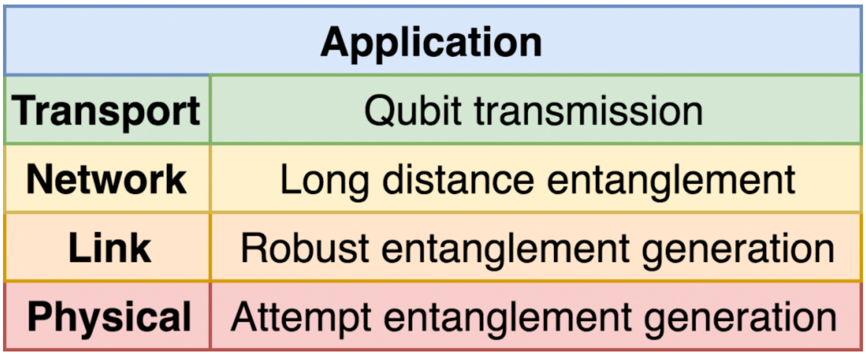
4.1.2 The quantum internet protocol

The Quantum Internet protocol does not send bits (or qubits) across the network like the TCP/IP does. Sending a qubit, which can for example be encoded as the polarization of a single photon, is not possible over long distances yet. This is due to the fact that the probability of losing the photon in the fibre is exponential. In the classical internet, the information is copied from one node to the next, which is not possible in a quantum stack because of the no-cloning theorem [19]. This theorem forbids the creation of identical copies of an arbitrary unknown quantum state, considering the laws of quantum mechanics. This makes it almost impossible to send qubits or photons across the network due to the high probability of losing it. Instead, the Quantum Internet protocol is based on entangled links within the network. One of the protocols that can be executed is teleporting the qubit from one node to another via the entangled link and sending two classical bits. There are many more applications in which the entangled link is used, identified by Wehner et al. [7]. Examples of those applications are: secure communication, clock synchronization, extending the baseline of telescopes, secure identification, achieving efficient agreement on distributed data and more.

Another difference between the classical and quantum protocol is that such an entangled link (connection between two nodes) can only be used once. After it is used, the entangled link is gone and should be established again. In addition to this, the connection between two nodes requires continuous participation of two nodes. This means that all the layers participating in the connection can only work for that connection, and do nothing else in the meantime. The same holds for the participating nodes, which are occupied during the whole lifetime of the entangled link.

4.1.3 The quantum network stack

In the paper of Dahlberg et al. (2019) a setup of the network stack for the quantum devices is proposed [1]. This setup is depicted in figure 4.1. It is inspired heavily by the classical internet stack. In the physical layer, entanglement generation attempts are performed between directly connected nodes. Generating entanglement is something that takes multiple attempts before it is successful; the rate depends on the bright state probability α and probability of detection (p_{det}) and can take up to 20000 attempts for one entangled link at maximum fidelity on our platform [5]. This influences the way the link layer is working in the quantum stack. The link layer has to keep track of the state of the entanglement generation requests from higher layers and make new attempts at the physical layer. Therefore, the service of the link layer is to provide the network layer with robust entanglement generation between two directly connected nodes. Extending entanglement to other nodes, at a distance and without a physical connection in the network, is the task of the network layer.



Application	
Transport	Qubit transmission
Network	Long distance entanglement
Link	Robust entanglement generation
Physical	Attempt entanglement generation

Figure 4.1: ***View on quantum network stack.*** *The quantum network stack is inspired by the classical internet stack and consist of five layers with each their own task in the system. Adapted from Dahlberg et al. [1].*

4.2 Communication between link-layer and physical layer

The goal of this research is to establish the communication between the link layer and physical layer and fulfil requests coming from the link layer in real-time. Besides only fulfilling the requests, the quantum nodes should be left in a state that allows them to execute the following request. This can be while waiting for the next request, the qubits must be protected from decoherence.

Although the physical layer is build to be able to execute all pre-defined requests, they cannot always be performed. This can be due to the hardware not being ready, not enough qubits available, etc. When this is the case, the physical layer should let the link layer know, without the system breaking off.

The physical layer used in this research has two separate quantum nodes, based on NV centres in diamond, both consisting of all the instruments shown in figure 3.3. For the communication with the link layer, the ADwin of this setup is used. The ADwin, a microcontroller (MCU) is a real-time processor with analogue and digital inputs and outputs connected to it. To manage this processor, a special development environment — ADbasic — is used. The processor and development environment, together with the communication with a PC and drivers to graphical user interfaces, are able to control the setup in real-time. The operations that can be done with this system are in the range of microseconds. This MCU is used to control the other devices in the experimental setup. Furthermore, each node has an arbitrary waveform generator (AWG) that handles nanosecond timescale operations (such as qubit gates).

For the link layer, the group of Stephanie Wehner at QuTech developed an operating system that has all the functionalities it should have for the link layer. From now on, when referring to the link layer, this operating system is meant. The MCU in the physical layer communicates with the link layer. The link layer passes on the operations the application wants to do in commands that the MCU can execute. It is not important for the link layer to know how the MCU executes these commands. The idea behind the different layers is that they can execute their own protocols and only pass on the results to each other.

4.2.1 Connections between physical layer and link layer

To establish the connection between the physical layer and the link layer, multiple devices are needed. Each quantum node, has its own instruments to control its NV centre. Besides, each quantum node has its own network controller which performs the link layer protocol proposed by Dahlberg et al. [1]. The MCU per node is used to communicate to the network controller, but also to communicate to the MCU of the other node. This last communication connection is only needed for synchronization purposes at entanglement requests. All the other communication between the two quantum nodes is executed by the link layer over a LAN (local area network). In figure 4.2 the schematic overview of the two quantum nodes is displayed.

4.2.2 Communication interface

A Serial Peripheral Interface (SPI) is used for communication between the link layer and the MCU. SPI is a synchronous serial data link between at least two media. There is initially one master and one slave. In this research, the link layer is the master and the physical layer the slave. Communication between master and slave takes place in full duplex at all times. Full duplex communication means that a connection can be established in which information is exchanged simultaneously in both directions: from master to slave and from slave to master. This can be done by using two separate parallel connections [20]. In the current setup, a communication cycle of 50 kHz is used. This means that the physical layer pulls a new instruction from the link layer every 20 microseconds.

The communication coming from the link layer to the MCU is done in commands. These commands instruct the MCU on which experimental step to take. Examples of these commands are qubit initialization, performing a gate (rotation of the qubit over a certain axis [X, Y, Z] and over a certain angle θ), entangle two qubits and measuring the qubit.

After each command the link layer sends to the MCU, the MCU will try to execute that command. After it has been executed, the MCU will tell the link layer the result. For these outcomes, there are also limited possibilities that can be communicated, so the link layer knows what the sent outcome means. Besides the outcomes success or failure — for initialization and gate commands — it is also possible to send specific outcomes for the Bell state of the created entanglement and if the measurement outcomes are zero or one ($|0\rangle$ or $|1\rangle$ in Z basis).

Available commands

As stated before, the commands the link layer can send to the physical layer are predefined. When an unknown command is sent to the physical layer, it sends back a failure. This means that the physical layer has done nothing and is waiting for a new command. At the moment, there are 7 commands pre-defined in the communication. These commands are:

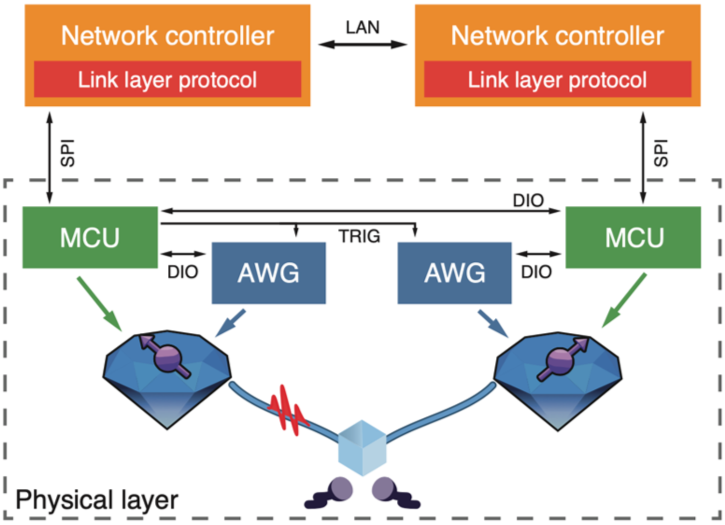


Figure 4.2: ***The connections between the two quantum nodes via the link layer.*** *Each quantum node has its own network controller, which implements the link layer protocol in the system. The network controller communicates with the microcontroller (MCU) of the physical layer via a serial peripheral interface (SPI). The MCU controllers the other instruments in the physical layer, including the arbitrary waveform generator (AWG). This control is done by applying voltages. The AWG delivers microwave pulses to the qubit. Via a digital input-output (DIO) interface, the MCU's of both nodes can communicate for synchronization purposes, needed for entanglement generation. Both MCU are driven by a shared clock of 1* MHz*. To be able to start the entanglement generation sequence simultaneously, the MCU of the first node is connected to the AWG of the second node via a dedicated trigger channel (TRIG). Both quantum devices have the ability to emit photons that are entangled with the electronic spin of the NV centre, the communication qubit. On a beam splitter, the photons from the two nodes are combined. At the other side of the beam splitter, two single-photon detectors herald the generation of remote entanglement between the communication qubits of the two quantum network nodes.*

- **No Operation (NOP)**
  Due to the defined communication cycle, it occurs that the MCU at some point has nothing to execute. The MCU remains inactive until the next communication cycle, when it pulls a new request from the link layer. If there are no operations available from the link layer, a NOP is executed, which means just waiting for the next communication cycle.

- **Initialize qubit (INI)**
  The initialization of the qubit in the $|0\rangle$ state is executed when getting the INI command. This initialization can be done optically by shining a laser $\approx$100 μs to the NV centre, so the system will excite when it is in the $m_S = \pm 1$ state and at some point fall back into the $m_S = 0$ ground state. This moves the population into $|0\rangle$ with a very high probability [5]. Therefore, the outcome send back to the link layer is always successful.

- **Single qubit gate (SQG)**
  The single qubit gate command the link layer asks for, is a rotation gate which consist of an angle θ around either the X, Y or Z axis of the Bloch sphere. Although θ covers the whole 2π range, not every angle θ can be executed precisely. The range is divided in 32 steps, with a resolution of $\pi/16 = 11.25°$. In the case of an X or Y rotation (native gates), the gate consist of a microwave pulse generated by the AWG, which is delivered to the qubit. Before being sent down to the physical layer, non-native gates like a Hadamard or a NOT are compiled into combinations of native gates by the link layer.
  Now, only X and Y rotations are possible, but doing Z rotations belongs to the first next steps to take. To do them, the AWGs internal oscillator keeps track of the accumulated Z phase and apply new pulses with proper IQ signal modulation. After gate execution, the physical layer always sends

a success outcome to the link layer.

- **Measure qubit (MSR)**
  In order to measure the qubit, a laser that is only resonant with the $|0\rangle$ state of the qubit is used. By shining the laser shortly to the qubit, it will be excited if it is in the $|0\rangle$ state and falls back by emitting a photon. We assign the 0 outcome when at least one photon is detected in the fluorescence of the NV centre. We assign the 1 outcome if no photons are observed. The outcome of the measurement on the communication qubit in the computational basis (either 0 or 1) is communicated to the link layer.

- **Entangle and keep (ENT)**
  Unlike the processes described above, which are single qubit processes, producing entanglement necessitates precise synchronization between the two nodes. Therefore, before trying to make entanglement, the MCUs first start a synchronization process in which they use bidirectional communication to achieve μs-synchronization. Next, a phase stabilization procedure is executed to obtain optical phase stability. This procedure is identical to the one used by Pompili et al. [5], but then executed over two nodes instead of three. At this point the setup is ready to attempt to generate entanglement, therefore the MCU of the first node triggers the entanglement sequence on both AWGs. This is done by one MCU to achieve nanosecond synchronization of the entanglement attempts. The AWGs attempt a specified number of entanglement attempts (1000 in this research), before declaring failure to the MCUs. If all entanglement attempts fail, the MCUs notify the link layer of the entanglement failure. If one of the entanglement efforts succeeds, a fast digital signal is sent to both AWGs and MCUs, preventing the next entanglement attempt from being played (which would destroy the produced entangled state). When the AWG receives this signal, it starts an XY8 decoupling sequence to preserve the entangled state. The Bell states that can produced in the setup are either Ψ^+ or Ψ^-. The MCU communicates to the link layer that an entangled state is generated and which of the two Bell states it is. The nodes are now actively protecting their qubits against decoherence and are ready to receive further commands, like rotation gates or doing a measurement.

- **Premeasurement gate (PMG)**
  In addition to generating entanglement and then maintaining the state while waiting for further commands, the rotation gates and measurement to be executed after entanglement generation may also be sent in advance. Therefore, before sending an entangle and measure (ENM) request (explained below) a premeasurement gate should be sent. This PMG command consist of three angles, the first around X, the second around Y and the third again around X. These angles are stored in the MCU, so they can be executed whenever an ENM command is requested. After storage, the MCU communicates success to the link layer, indicating that it is ready for further commands.

- **Entangle and measure (ENM)**
  The entanglement and measure command is executed as a combination of entanglement generation, single qubit gates and a measurement command at the physical layer. First, the normal entangle and keep (ENT) action is executed, then the gates saved from the premeasurement gate command (PMG) are performed and finally a measurement (MSR) is done. This is done all without intermediate communication between the link layer and physical layer. The result the MCU send to the link layer consist of the entangle state generated (Ψ^+ or Ψ^-) and the outcome of the measurement (0 or 1).

4.2.3 Establish communication

Before being able to execute any command coming from the link layer, the physical layer first should do a charge and resonance check (CR check). This operation is unique to the NV center, and it entails shining the qubit-controlling lasers on the diamond device while monitoring its optical response to ensure that the NV center is in the correct charge state and in resonance with all the lasers. When it does not pass the check, it will keep testing till it succeeds. The physical layer becomes available and starts pulling new commands from the link layer if this check is passed. This CR check is not only done at the very start of each experiment. When the NV centres passes the CR check, but doesn't get any commands from the link layer for 100ms (in this setup), the MCU goes back into CR checking before making itself available again to the link layer. This has two reasons: a successful CR check does not have infinite validity because spectral diffusion caused by undesired control forces (optical and electric) might cause the NV center to shift out of resonance. Second, background routines that keep the lasers in resonance with the NV center (and vice versa) require a steady stream of data regarding the resonance condition. The validity of the CR check is timed out after 100 milliseconds, ensuring that the device is available and in the correct state, so it can be used when needed.

The way the MCU works, is that it can run a script every (in our case) microsecond. This script is the same in every cycle, but the task the MCU performs differs. In each cycle, the status of the MCU should be set to the status of the next step in the process. To make it more complex, multiple process exist in the same MCU script, these are called state machines. These state machines all contain a separate code for a different task in the experiment. In this research, the issue is not how MCU executes each of these processes, but the link layer tells MCU which processes to execute. To get an idea of how these processes are connected, the overview of the state machines is shown in figure 4.3.

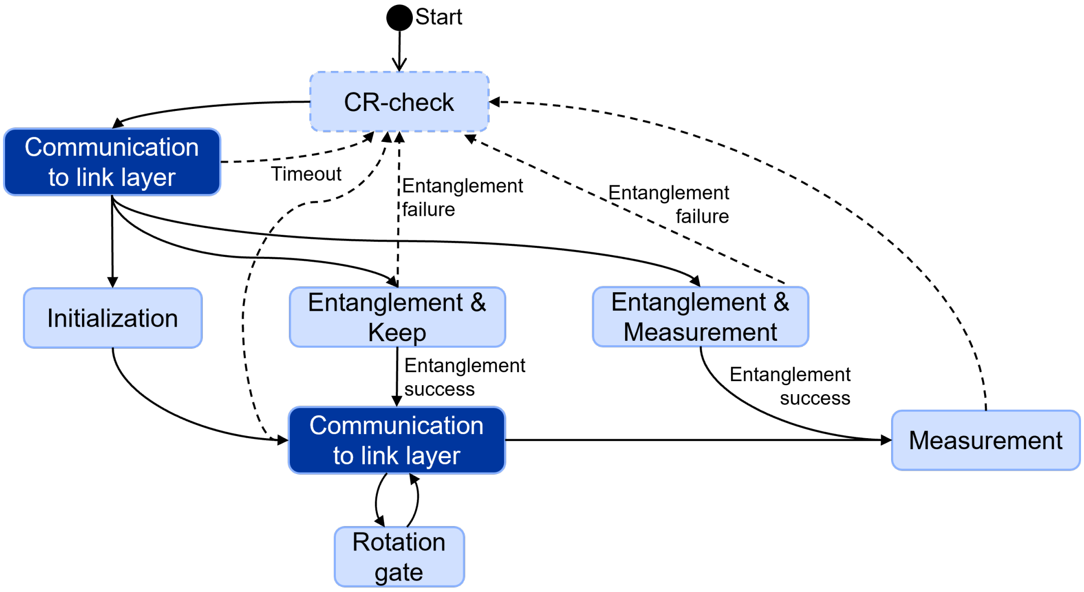


Figure 4.3: ***An overview of the state machines in the MCU.*** *Each light blue bar represents an individual state machine, and the dark blue bars are the states in which the MCU communicates to the link layer. The link layer always has to wait until the MCU successfully passes the CR check and is available to receive commands. After a successful CR check, the MCU can accept the commands for initialization, entanglement & keep and entanglement & measure. If one of the first two is executed successfully, the MCU can accept new commands from the link layer, namely to execute a gate or to make a measurement. If a measurement has been made, the generation of entanglement has failed or the link layer does not send commands to the MCU in time, the MCU becomes unavailable for the link layer and performs a new CR check.*

4.2.4 Demonstration of the communication

To be able to generate platform-independent entanglement, the communication between the link layer and the physical layer should work correctly. Therefore, the commands the link layer sends to the physical layer should be handled correctly by the MCU. This includes going into the right state machine, depending on the command received, and sending back the proper outcome.

In the communication between the link layer and the MCU, each command must be followed by a result before the next command is sent. This is because the command the link layer sends next depends on the outcome of the previous command. For example, if the link layer wants to establish entanglement and the physical layer fails to do so within 1000 attempts, it sends back the result "entanglement failed". The next command of the link layer must again be an entanglement command. If, on the other hand, the physical layer succeeds and sends the entangled state Ψ^+ as an outcome, the next command of the link layer should not be another entanglement command, but a rotation gate or measurement command, depending on the application the link layer is performing. The communication traces between the link layer and MCU are schematically presented in figure 4.4.

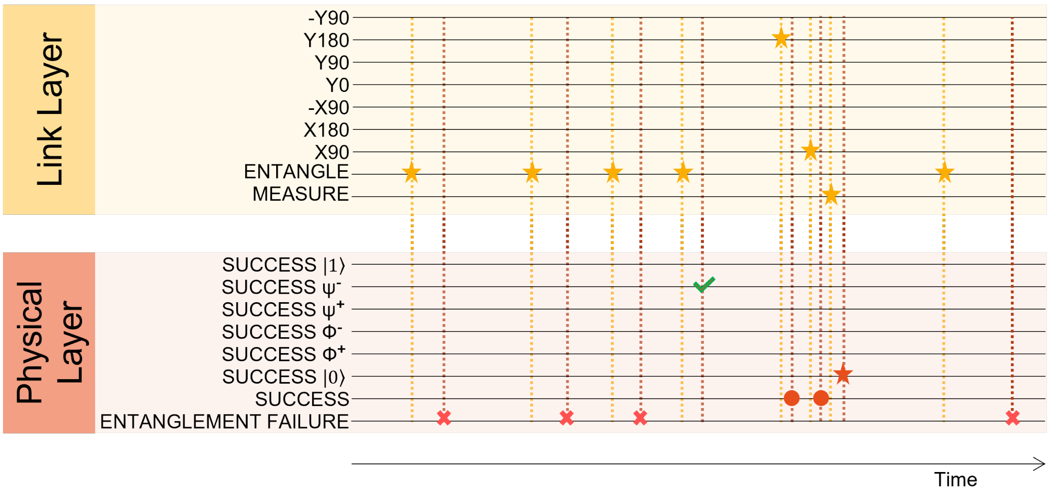


Figure 4.4: ***Representation of communication traces between link layer and physical layer during entanglement generation.*** *After each command sent by the link layer to the MCU, the physical layer attempts to execute that command. After each execution, the physical layer sends the result back to the link layer. Depending on this result, the link layer decides which command to execute next. Not all possible commands and outcomes are displayed (see main text).*

The communication traces shown in figure 4.4 are from a single setup. Each setup has its own link layer and physical layer, and therefore its own communication traces. In the figure an example of executing an application is shown. For that application, first entanglement should be made and based on the outcome of the entanglement generation a gate is performed and the qubit is measured. The entanglement command in the figure is the entangle & keep command. This command is needed to be able to execute certain gates, which are determined based on the entangled state. In the figure, it can be seen there is some delay between the physical layer sending the entangled state as outcome to the link layer and the moment the link layer send the next command; in this case, a rotational gate of 180 degrees about the Y-axis. This is due to the processing time in the link layer, deciding which gate(s) to do next.

For rotational gates, a total of 64 (32 steps of θ to cover the 2π range for both X and Y) different possibilities are available. All these rotation commands are a single qubit gate command, including the angle θ and axis (X, Y or Z) of rotation. Not all 64 possibilities are shown in figure 4.4 for the sake of clarity.

The application run by the link layer only needs to make a measurement after the rotational gates have been executed. The time between the last executed gate and the command for the measurement is short, because the link layer does not have to decide what to do based on previous results, but only has to perform a measurement. When the measurement is done and the entanglement is vanished, the physical layer becomes again available for entanglement generation. Between the measurement and the next entanglement request, the link layer is performing a CR-check. This isn't visible in the graph, since the link layer and physical layer do not communicate about it. The reason for this is that the physical layer only becomes available for new commands when the CR-check is passed. So, when seeing a new command appearing from the link layer means the CR-check was successful and the node can be used for a new application.

In figure 4.4 the commands coming from the link layer are successfully executed by the physical layer, but there are situations in which the physical layer is not able to execute the command. There are multiple reasons why that can happen, examples are: an unknown failure, a hardware failure (both on the physical layer's side), the link layer has sent an unsupported command to the physical layer or is asking for an action on an invalid qubit. This last one has to do with the fact that at the moment of writing the physical layer can only control the communication qubits of the nodes, but in the future it should also be able to control the memory qubits present in the neighbourhood of the NV centres in the diamonds.

Chapter 5

Capabilities of our quantum network stack

In order to evaluate the capabilities of our quantum network stack, three quantum network tasks are performed. These tasks are: platform-independent full state tomography of the delivered states, real-time selection of latency and fidelity, and remote state preparation of a qubit on a server by the client. In the following sections the goals of each task are explained and in the next chapter the results of each task can be found.

There is one note to be made about the entanglement generation via the link layer with the NV centres as platform throughout all applications: The Bell states that can produced in the setup are either Ψ^+ or Ψ^-, depending on which detector saw the photon in the single photon protocol. The link layer of the client node requests a correction gate (either a X_{180} or a Y_{180}) to always obtain $|\Phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$. This is done as a courtesy to the quantum network programmer, who is assured the same Bell state at all times and does not need to incorporate Pauli corrections in the high-level application description.

5.1 Full state quantum tomography of the delivered states

The first thing that's performed to evaluate the capabilities of our quantum network stack is full quantum state tomography. Quantum state tomography is used to reconstruct the entangled state from measurements on an ensemble of identical quantum states. Therefore, high-fidelity entangled states need to be generated, and the tomography should be performed in a platform independent way. The ensemble of measurements consists of all 9 two-node correlators, along with all possible positive and negative basis combinations, to minimize the bias due to our asymmetric measurement errors. This give the following 36 combinations:

$$\begin{array}{llllll}
\langle -X-X\rangle, & \langle -X-Y\rangle, & \langle -X-Z\rangle, & \langle -X+X\rangle, & \langle -X+Y\rangle, & \langle -X+Z\rangle\,, \\
\langle -Y-X\rangle, & \langle -Y-Y\rangle, & \langle -Y-Z\rangle, & \langle -Y+X\rangle, & \langle -Y+Y\rangle, & \langle -Y+Z\rangle\,, \\
\langle -Z-X\rangle, & \langle -Z-Y\rangle, & \langle -Z-Z\rangle, & \langle -Z+X\rangle, & \langle -Z+Y\rangle, & \langle -Z+Z\rangle\,, \\
\langle +X-X\rangle, & \langle +X-Y\rangle, & \langle +X-Z\rangle, & \langle +X+X\rangle, & \langle +X+Y\rangle, & \langle +X+Z\rangle\,, \\
\langle +Y-X\rangle, & \langle +Y-Y\rangle, & \langle +Y-Z\rangle, & \langle +Y+X\rangle, & \langle +Y+Y\rangle, & \langle +Y+Z\rangle\,, \\
\langle +Z-X\rangle, & \langle +Z-Y\rangle, & \langle +Z-Z\rangle, & \langle +Z+X\rangle, & \langle +Z+Y\rangle, & \langle +Z+Z\rangle
\end{array}$$

After generating an entangled state, rotational gates are applied to the first and second node. The rotational gate that is applied depends on the measurement base that is wanted to be used, and both nodes can therefore receive a different rotational gate. Reading out in the +X base requires a different rotational gate compared to reading out in +Y. This means that the nodes' rotational gates are determined for both nodes per measurement. Each combination is measured 125 times, to achieve a data set of in total $36 \times 125 = 4500$ entangled states generated. To eliminate biases in the read-out, the measurement bases are alternated instead of measuring the first 36 times before going to the next.

5.2 Real-time selection of fidelity

The capability to trade off fidelity for rate is one of the properties of the single photon protocol that is used to create entanglement: it is feasible to generate entangled states at a faster rate at the expense of a lower fidelity. This is an important property, since the link layer requests not only entanglement generation, but also a real-time fidelity of the generated entangled state. This requested fidelity should be processed by the MCU, to be able to deliver the requested entangled state. The MCU forwards the targeted fidelity to the AWG, which will perform one of several pre-calibrated entanglement sequences that generate entangled states with the correct target fidelity. The AWG does this by varying the α-pulse from equation 3.4, to change the occupancy of the $|0\rangle$ state. The higher the value of α, the higher the occupancy of the $|0\rangle$ state, which leads to an increase in rate but a decrease in fidelity. So the higher the requested fidelity, the lower the achievable rate in entanglement generation. This feature is especially valuable in a network setting, where certain applications may want very high fidelity entanglement and are willing to wait a long time for it, while others may prefer a higher rate at the cost of lower fidelity states [1].

To demonstrate this capability of the link layer, not all nine correlators as in the full state tomography are measured, but only the $\langle XX\rangle$, $\langle YY\rangle$ and $\langle ZZ\rangle$ correlators. It is enough to only measure those to determine the fidelity of the entangled state. The $\langle XX\rangle$, $\langle YY\rangle$ and $\langle ZZ\rangle$ correlators come along with all possible positive and negative basis combinations to minimize the bias due to measurement errors, which gives a total of $3 \times 4 = 12$ measured correlators. Each of these correlators is measured with seven different target fidelities for its entangled states: 0.50, 0.55, 0.60, 0.65, 0.70, 0.75 and 0.80. Per fidelity 1500 entangled states are generated, for a total of 10500 delivered states. It is worth noticing that the measurement loops through the targeted fidelities in real-time, to eliminate bias in the measurements, and the physical layer is ready to deliver any of them at any time.

5.3 Remote state preparation on a qubit

For this task, the two nodes are not equally treated, but one is used as a client and the other as the server. This has to do with the goal of the applications of remote state preparation (RSP). In remote state preparation, a state is prepared on the server's qubit by the client. This comes in useful when it is possible to perform computations on a remote quantum server, because remote state preparation allows a client to keep the computations performed private while running quantum applications on a powerful quantum server using all the qubits the server has [21]. The capability of the link layer we want to demonstrate is that the client can prepare states remotely on the server with sufficient fidelity.

For the remote state preparation, the link layer first sends a premeasurement gate to the client node. Next, it sends an entangle & keep (ENT) command to the server node and an entangle & measure (ENM) command to the client node. In this way, the client performs the rotational gates and measurement, in which it creates the state on the server immediately after entanglement is generated. Because of the premeasurement gate (PMG) send prior to the entangle & measure command, the client knows in advance in which basis the created state is going to be. Since there is no communication needed between the link layer and the MCU during the entanglement creation, performing the rotational gates and the measurement the entangle & measure command saves time compared to the entangle & keep command.

Based on the entangled state and the measurement outcome, the client knows in which state the server can be found. In principle, the link layer knows this state as well and can perform other rotations on the server qubit, according to the computation the client wants to do. In this experiment, the link layer is alternating between the measurement bases on the server, independently of the measurement outcome of the server. This is because the main goal is to determine whether the state that the client thinks it has created was actually created on the server, and what the fidelity of that state is.

In figure 5.1 an example trace of a part of the remote state preparation is shown. It can be seen that the client node (node 2) gets an entangle & measure command and the server node (node 1) the entangle & keep command. It is also noticeable that the server nodes starts doing rotational gates after the client node has performed the measurement. So the server node is waiting for having a state prepared on it by the client.

In principle, the server does not have to wait in this case, as only the tomography is performed on the server. This means that the server can measure immediately. With blind quantum computation (BQC), instead of just using your own quantum computer, calculations can be outsourced to quantum servers that do the work for you - the client sends classical messages to the server. This implies that the server has to wait there to measure until it receives the result from the client [21].

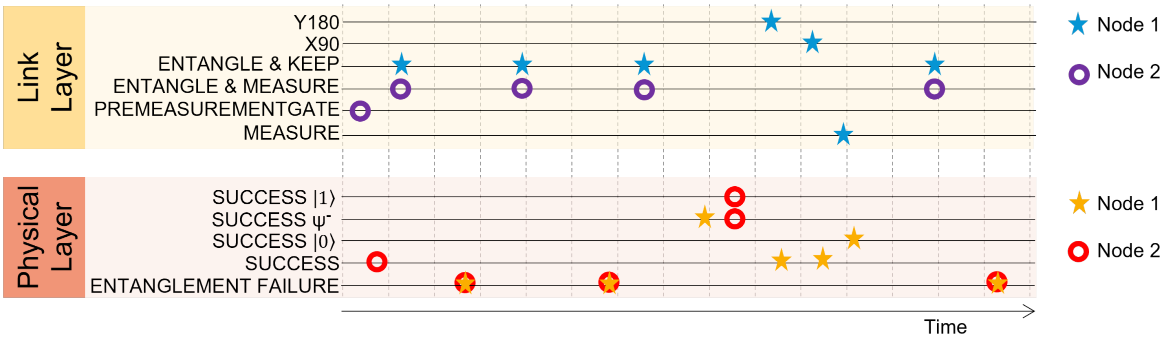


Figure 5.1: ***Representation of communication traces between link layer and physical layer during remote state preparation.*** *Node 2 (the client node) receives an entangle & measure command, whereas node 1 (the server node) receives an entangle & keep command. It's worth noting that for doing blind quantum computation, the server nodes have to wait till the client node has completed the measurement and sends the outcome to the link layer. As a result, the server node is waiting for the client to prepare a state on it.*

Chapter 6

Results and discussion

To test the capabilities of our quantum network stack, we run different applications (set/order of commands). The physical layer does not know which of the applications the link layer is running, it just executes the commands it gets, exactly how the quantum network stack is designed [1].

6.1 Full state quantum tomography of the delivered states

To get the most likely density matrix of the full state quantum tomography, the measured data is corrected for known measurement errors at both nodes as well as the elimination of cases in which at least one of the two nodes had an incorrect charge state (the CR check after reports zero counts) in order to obtain the most faithful estimate of the generated state. The method to do this is identical to the method used by Pompili [22].

Although, it is beneficial to compensate for these errors in order to obtain the most accurate reconstruction of the delivered states, in a real network environment such errors are unavoidable. The corrections for the known measurement errors can only be done in post-processing, which means the analysis carried out to obtain the full state quantum tomography needs to know that the measurements contain errors and how those should be compensated for. However, for the incorrect charge state correction it might be possible to do in real-time, although not yet applied in our experiments. Since the information about whether to discard an entangled pair is only available at the physical layer after the entangled state is delivered to the link layer (when the next CR check is performed), applying the correction for the incorrect charge states directly at the link layer may prove challenging for arbitrary applications that use the delivered entangled states for something other than statistical measurements. However, after entangled states have been delivered by the physical layer, a mechanism to identify bad entangled pairs retrospectively at the link layer — like the expiry feature included in the initial design of Quantum Entanglement Generation Protocol [1] — could be used to discard them.

To be able to reconstruct the density matrix of the full state quantum tomography, the python package QInfer [23, 24] is used. The Monte Carlo method for Bayesian estimation of density matrices from tomographic measurements, as described in Ref. [25] has been carried out.

Through this analysis, the density matrix of the entangled state can be reconstructed. This matrix is displayed in figure 6.1. The exact values and uncertainties of this reconstructed density matrix are:

$$\mathrm{Re}[\rho] = \begin{pmatrix} 0.442(6) & 0.003(3) & 0.003(2) & 0.328(5) \\ 0.003(3) & 0.033(6) & -0.023(5) & -0.000(5) \\ 0.003(2) & -0.023(5) & 0.056(4) & -0.003(4) \\ 0.328(5) & -0.000(5) & -0.003(4) & 0.469(7) \end{pmatrix}$$

$$\mathrm{Im}[\rho] = \begin{pmatrix} 0 & -0.014(3) & -0.005(7) & 0.032(5) \\ 0.014(3) & 0 & -0.002(4) & 0.001(5) \\ 0.005(7) & 0.002(4) & 0 & -0.000(7) \\ -0.032(5) & -0.001(5) & 0.000(7) & 0 \end{pmatrix}$$

Here $\rho_{ij,mn} = \langle ij| \rho |mn\rangle$, with *i,m (j,n)* being the client (server) qubit states in the computational basis. Each element of the density matrix has an uncertainty, which is calculated as the standard deviation of that element over the probability distribution approximated by the Monte Carlo reconstruction algorithm (probability distribution approximated by 1×10^5 Monte Carlo particles [25]).

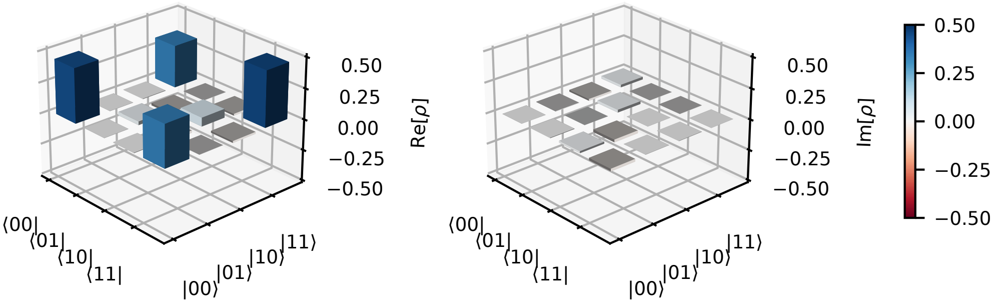


Figure 6.1: ***Link layer generated full state quantum tomography.*** *The entangled states delivered by the link layer are measured in all possible two-node correlators.* ***Left:*** *The real part of the reconstructed density matrix ρ obtained from this entangled state.* ***Right:*** *The imaginary part of the same reconstructed density matrix ρ. The uncertainty on each element is $\approx 0.5\%$.*

From the data of the reconstructed density matrix, an estimation of the fidelity of the delivered entangled states with the maximally entangled Bell state can be made. This fidelity is $F = 0.783(7)$. This number comes close to the fidelity of the entangled states between these two nodes measured before by Pompili et al. [5]. Their fidelity is approximately 1.5% higher than the fidelity delivered by the link layer.

We believe the decrease in fidelity is due to the extra time required to decouple the entangled state in order to perform real-time operations. When using the link layer, after entanglement generation, a decoupling sequence is started to prevent the entangled state from decoherence. While the link layer and physical layer are communicating about what to do next, the decoupling sequence is played till there is a next action to do. Besides, in between commands from the link layer, like multiple gates, at least one decoupling sequence is done. This means, compared to delivered fidelity without the use of the link layer, more decoupling sequences are played. The longer the entangled states needs to be preserved, the more it will decohere. Longer evaluation times, result in a lower fidelity, as explained in figure 3.5.

In addition, the correction gate applied to always deliver the $|\Phi^+\rangle$ state may also reduce the fidelity. Converting $|\Psi^+\rangle$ or $|\Psi^-\rangle$ always into $|\Phi^+\rangle$ requires a correction gate: either a X_{180} or a Y_{180}. These rotational gates are calibrated, but are not fully perfect. This means that doing a π-rotation, takes extra time (more decoupling sequences needed) and because of its imperfection, lowers the fidelity of the entangled state. More research would need to be done to determine exactly where the additional infidelity from using the link layer comes from.

6.2 Real-time selection of fidelity

To determine the characteristics of the fidelity delivered by the link layer, two things are of interest: First, how well does the fidelity of the entangled state delivered by the link layer match with the requested fidelity. Secondly, what is then the relation between the fidelity and rate. We expect to see a lower rate of entanglement generation, when the requested fidelity is higher [4].

6.2.1 Measured fidelity versus requested fidelity

In figure 6.2a the requested fidelity versus the measured fidelity is plotted. Together with the entanglement request, the link layer sends the requested fidelity of the entangled state. By varying the value of the α-pulse in real-time, the fidelity can be changed. For each of the available fidelities, the α-pulse is calibrated accordingly. To prevent biases in the result, the different fidelities are requested alternately.

The grey dashed line in figure 6.2a is the $y = x$ diagonal. The grey dots are the target fidelity values in the physical layer. These target values are set 3% higher than the requested fidelity to be sure the requested fidelity is always reached. This is done to compensate for possible calibration errors in the α-pulse. From the figure, it can be concluded that the fidelity of the delivered entangled states comply with the requested fidelity. All measured fidelities are equal to or higher than the requested fidelity. This means the link layer is able to deliver different fidelities in real-time by adjusting the value of the α-pulse.

As with full-state quantum tomography, the data for the measured fidelities in figure 6.2a are corrected for known measurement errors at both nodes and incorrect charge states to obtain the most faithful estimate of fidelity. In the figure, also the measured fidelities that are not corrected for incorrect charge states are plotted. As expected, the fidelity reduces by a few percent when not corrected for the wrong charge state events. In Appendix A the exact values can be found for the data in the plot.

6.2.2 Requested fidelity versus latency

To determine the speed of delivery of the entangled state, we measure the latency of delivery: Latency is the time between the first entanglement request send from the link layer till the moment it receives the entangled state as outcome from the physical layer.

Figure 6.2b shows the average latency, including the contributions of the different sources. We excluded entanglement requests that took more than 10 seconds to complete for calculating average latencies. These high-latency requests are due to the NV center becoming off-resonant with the relevant lasers in the setup. The main contribution to the latency comes from the physical layer. This is expected, since generating entanglement is not done in a single attempt, but multiple attempts has to be done. The total time contribution of the physical layer is composed of the total time it takes to generate entanglement. This includes all steps the MCU needs to do for entanglement generation, also when it fails and have to start over again. These steps are displayed in figure 4.3. The major components of entanglement generation are:

- *The time it takes to do the entanglement attempts.* Each entanglement request from the link layer, results in a 1000 entanglement attempts. Doing a 1000 attempts takes $\approx$ 4ms.
- *Phase stabilization.* Each time the physical layer gets an entanglement request, it has to do at least one round of phase stabilization before it is able to start the 1000 entangling attempts. Doing one round of phase stabilization takes $\approx 150\mu$s.

If the physical layer fails to generate entanglement within the 1000 attempts it makes after each command, it informs the link layer that it has failed. The physical layer immediately makes itself unavailable for new commands, as it must perform a charge and resonance check to ensure that the NV is in the correct state to perform the next command. This CR-check takes about $\approx$ 1ms. Depending on how many attempts the physical layer needs to generate entanglement, the number of times it needs to perform a CR-check changes. For higher fidelity, entanglement generation requires more attempts, which means more blocks of 1000 attempts, interspersed with CR checks between each block. Therefore, in figure 6.2b, the contribution of the CR check increases as fidelity increases.

Next to the contributions of the physical layer, using the link layer protocol to generate entanglement imposes also a small overhead time. This latency contribution, of $\approx$ 10ms when the link layer protocol

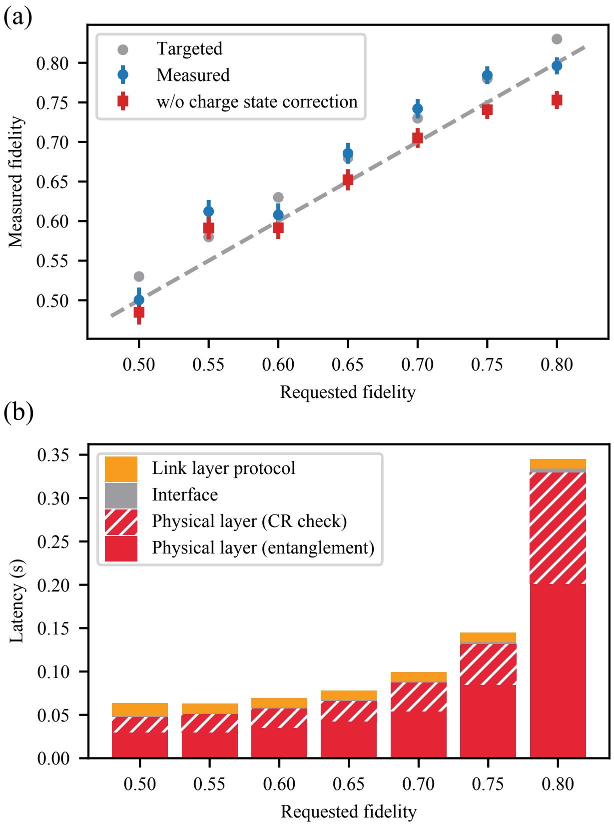


Figure 6.2: ***a) Measured fidelity versus requested fidelity.*** *For each of the seven requested fidelities, 1500 states are generated. The fidelity of these states is measured (blue), and the average is compared to the requested fidelity. The grey dashed line represents the $y = x$ diagonal. The grey dots are the set fidelity values in the physical layer; 3% higher than requested to be sure the requested fidelity is always reached. The measured fidelities without being corrected for incorrect charge states are plotted in red.* ***b) Requested fidelity versus latency.*** *The latency, showing all sources separately, is measured for different requested fidelity. The main part of the latency consists of entanglement generation, phase stabilization and CR checking (see main text). The entanglement generation procedure imposes a small but measurable overhead ($\approx 10ms$) when the link layer protocol is used, which is independent of the requested fidelity. The communication delays between the link layer and the MCU introduce negligible overall latency.*

is used, is independent of the requested fidelity. This is partly due to the synchronization between the two nodes before being able to start generating entanglement. The other cause lays in the real-time communication with the link layer, which is the main contribution to the latency. They can reduce this contribution by requesting multiple entangled states in one command, although this is not possible yet in the current setup.

The final source of latency is incurred by the interface between the link layer and the microcontroller unit. The contribution of this source is very low compared to the overall latency.

6.3 Remote state preparation of a qubit

To show that the client is capable of preparing a state on the server, all 36 possible correlators ($\langle XX\rangle$, $\langle XY\rangle$, ..., $\langle ZZ\rangle$ and their ± variations) are measured. Same as for the full quantum state tomography, each correlator is measured 125 times, which results in a total of 4500 data points. These data points are grouped by the states prepared on the qubit of the server, resulting in 6 data sets (prepared states:

$|+X\rangle, |-X\rangle, |+Y\rangle, |-Y\rangle, |+Z\rangle, |-Z\rangle$). Based on these data sets, the fidelity of the prepared states on the server can be determined.

In figure 6.3 the states measured by the server are plotted on the Bloch sphere. The client performs a measurement in one of the three cardinal bases (X, Y or Z) after the link layer delivers an entangled state. A different state is prepared on the qubit of the server, depending on the client's measurement outcome. For example, the entangled state prepared is $|\Phi^+\rangle$, the client measures in the $+X$ base and the outcome is 0 on its qubit, then the server's qubit is prepared in the $|+X\rangle$ state. When the outcome of the client in this situation is 1, the state of the server would be $|-X\rangle$. If the server now reads out in the $-X$ base, it should get 0 as an outcome (if the state was prepared perfectly and without any measurement errors). If the server measures in the $+X$ base, the outcome 1 is expected.

In this test, the measurement base of the server is independent of the state prepared on the server. This means even though the client prepares the server in $|-X\rangle$, the server measures in one of the six bases ($+X$, $-X$, $+Y$, $-Y$, $+Z$, $-Z$). If the server measures in the same base (either positive or negative) as the client prepared the state, the expectation value of the server's measurement is expected to be high. When the server measures in a perpendicular base, the expectation value of the server's measurement is zero. This is because there is no correlation between, for example, a state prepared in $|-X\rangle$ and measured in $+Y$. Then there is a 50-50 chance to measure 0 or 1.

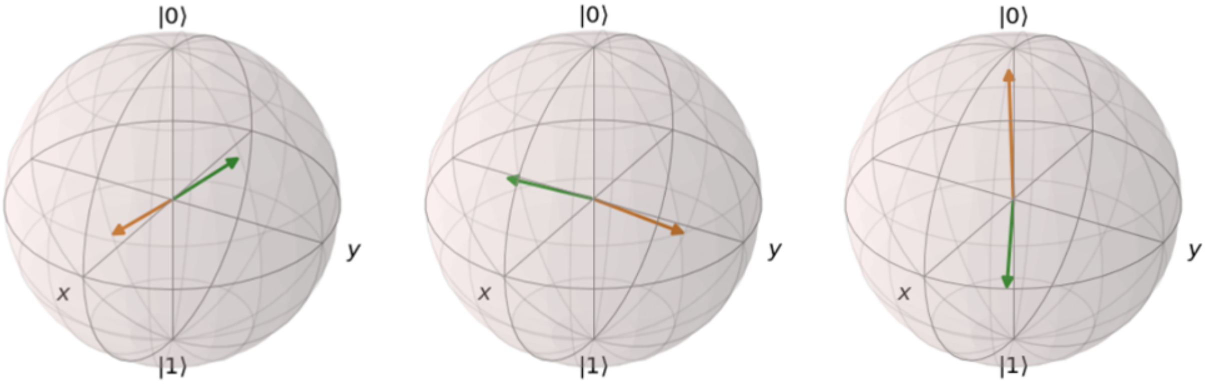
The expectation values of the X, Y and Z operator of the server's qubit are determined after accounting for the known server tomography error and removal of events in which either device was in then incorrect charge state [22]. These values are reported in table 6.1. The uncertainty on each of the measured components of figure 6.3 is reported in table 6.1 and is ≈ 0.05.

Table 6.1: ***Remote state preparation tomography.*** *The 4500 entangled states of the remote state preparation measurement are grouped by the states prepared on the qubit of the server, resulting in 6 data sets (prepared states by the client: $|+X\rangle, |-X\rangle, |+Y\rangle, |-Y\rangle, |+Z\rangle, |-Z\rangle$). For each data set, the expectation values for each server measurement basis are estimated. These values are corrected for the known server tomography error and removal of events in which either device was in then incorrect charge state. In the outer right column, the fidelity of the targeted prepared state is determined. The uncertainties of the expectation values and fidelities are displayed between parenthesis.*

Client	Server			
	$\langle X\rangle$	$\langle Y\rangle$	$\langle Z\rangle$	Fidelity
Measured $|+X\rangle$	0.634(48)	-0.123(62)	-0.004(59)	0.817(24)
Measured $|-X\rangle$	-0.645(43)	0.135(59)	0.030(63)	0.823(22)
Measured $|+Y\rangle$	-0.028(58)	-0.650(45)	0.005(61)	0.825(23)
Measured $|-Y\rangle$	0.026(65)	0.719(40)	-0.013(61)	0.860(20)
Measured $|+Z\rangle$	-0.081(65)	-0.083(66)	0.849(31)	0.924(16)
Measured $|-Z\rangle$	0.032(58)	-0.069(58)	-0.736(39)	0.868(19)

From table 6.1, one of the things that stands out is the asymmetry in the fidelity of the states prepared when the client prepared the server's state in $|+Z\rangle$ or $|-Z\rangle$. This is because the single-photon protocol used to generate entanglement has a double $|0\rangle$ occupancy error. This causes an asymmetry in the populations $\langle 01|\rho|01\rangle$ versus $\langle 10|\rho|10\rangle$ of the delivered entangled states.

The fidelity of the prepared states is affected by the measurement error of the client. This happens because when there is a measurement error on the client side, the state prepared on the server is misidentified. For example, when the client measures in the $+X$ base and get 1 as a result, the expected state prepared on the server is $|+X\rangle$. But when the measurement outcome of the server is client, due to measurement errors, the actual outcome should be 0. This means that the real state prepared on the server is $|-X\rangle$. In continuation, the expected measurement outcome of the server in the $+X$ base is 1, instead of the initial (without knowledge of the error) 0. There is no way to know if the measurement outcome of the client is the correct one in real-time, it can only be corrected for in the post-analysis.



(a) State prepared in $|\pm X\rangle$. (b) State prepared in $|\pm Y\rangle$. (c) State prepared in $|\pm Z\rangle$.

Figure 6.3: ***Remote State Preparation via the link layer.*** *When the link layer delivers an entangled state, the clients measures in one of the three cardinal bases (X, Y and Z). The outcome of this measurement influences the state prepared on the server's qubit. In the Bloch spheres, the states measured (orange =* $|+X/Y/Z\rangle$*, green =* $|-X/Y/Z\rangle$*) by the server are plotted. The uncertainty in these states is* ≈ 0.05*. The fidelity of the prepared state on the server is reduced by the measurement error of the client. Noise from the single-photon protocol in the entangled state causes an asymmetry in the* $|\pm Z\rangle$ *prepared states. More explanation can be found in the main text.*

Since the measurement error exists and cannot be completely eliminated, it must be handled so that all prepared states are affected equally. This is done by alternating between positive and negative readout orientations to ensure that the error does not bias the result.

In both figure 6.3 and table 6.1 events in which at least one of the two devices was in the incorrect charge state were again eliminated. From the expectation values for all different bases, the fidelity can be determined. These are stated in the last row of the table. The average fidelity of the remotely prepared qubit on the server is $85.3 \pm 0.8\%$.

Chapter 7

Conclusion and outlook

Throughout the work, the goal was to develop the physical layer of a quantum network stack. The layer of the network stack connected to the physical layer is the link layer. For entanglement-based quantum networks, we demonstrated the successful operation of a link layer and a physical layer. The physical layer's entanglement generation procedure—implemented here using two NV center-based quantum network nodes—is abstracted by the link layer into a robust platform-independent service that can be utilized to run quantum networking applications. Other quantum network platforms using the approaches provided here (which are not unique to our diamond devices) will accelerate the development of large-scale and heterogeneous quantum networks.

In order to determine the capabilities of our system, three quantum network tasks have been performed. The performed tasks were: platform-independent full state tomography of the delivered states, real-time selection of rate and fidelity, and remote state preparation of a qubit on a server by the client. All the tasks are tested successfully.

The fidelity of the full state quantum tomography is $78.3 \pm 0.7\%$, which is slightly less than previously reported on the same NV-based network nodes[5]. This is due to extended decoupling duration caused by the communication method used with the link layer.

The system shows to be able to deliver different fidelity states in real-time. The requested fidelities, asked from the link layer, are reached in delivery by the physical layer. Despite some minor inefficiencies — some of these issues can be addressed in a future protocol version (e.g. avoiding Pauli corrections unless necessary) — we have demonstrated that our implementation of the link and physical layers can deliver entangled states with the fidelity requested by the user.

The higher the requested fidelity, the higher the latency of the entangled state becomes. The latency got contributions of the entanglement generation ($\approx$ 4ms per 1000 attempts) and CR-check ($\approx$ 1ms in between blocks of entanglement attempts) of the physical layer, the use of the link layer protocol ($\approx$ 10ms) and the interface between the link layer and MCU (almost negligible). Increasing the amount of entanglement attempts that can be done per block, by improving the decoherence time of the NV in the setup, can decrease the latency. Besides, the contribution coming from the use of the link layer can be reduced by requesting multiple entangled states in one command, although this is not possible yet in the current setup.

Via the link layer, it is possible to create a state on the 'server' node while using the 'client' node. This is demonstrated in the remote state preparation test. In average, the fidelity of the remotely prepared state is $82.9 \pm 2.1\%$. The main sources of infidelity are the measurement error of the client and the noise from the single-photon protocol in the entangled state causes an asymmetry in the $|\pm Z\rangle$ prepared states.

7.1 Outlook

I am happy that we were able to demonstrate entanglement using a quantum network stack in this thesis. Several suggestions for improvement are provided below in order to continue and improve this research.

7.1.1 More options for rotational gates

All rotation commands are a single qubit gate command, including the angle θ and axis (X, Y or Z) of rotation. At the moment, a total of 64 (32 steps of θ to cover the 2π range for both X and Y) different possibilities are available for doing rotations. The I(Q) channel of the microwave vector source is used to select the X(Y) rotation axis.

A near-future improvement would be adding the option to do rotation gates around Z. Our physical layer currently does not support Z axis rotations, even if they are supported at the link layer. Virtual rotations of the Bloch sphere could be used to construct such rotations around the Z axis: a π pulse around the Z axis is equivalent to multiplying future I and Q voltages by -1. One can execute effective Z rotations with very high resolution and nearly no infidelity by keeping track of the accumulated Z rotations and modifying I and Q mixing correspondingly. The AWGs currently in use have the necessary capabilities, and Z gates will be implemented in the near future.

7.1.2 Reduce waiting times

Due to the addition of the link layer, the timings in between actions (entanglement generation and doing a rotational gate for example) isn't ideal any more. In the experiments from Pompili et al. [5] and Hermans et al. [6] the timings are optimized to reach the highest possible fidelity. The link layer adds a new action to those experiments, namely the communication between the link layer and the physical layer. This new action implies that the timings can not be set in advance, in which they lose the property of being ideal. The minimization of the extra time by cause of the link layer is needed to get the highest possible fidelity. There are a couple of sources of overhead time:

The communication cycle between the link layer and physical layer has now a frequency of 50 kHz. This means that the physical layer pulls a new instruction from the link layer every 20μs. This also implies that if the MCU on the physical layer has done its task within these 20μs, it has to wait (do nothing) till the next cycle. Besides, on the link layer side, there is also time needed to process the outcome send from the physical layer and decide on what to do next.

The main source of infidelity in the full state quantum tomography is the extra time required to decouple the entangled state in order to perform real-time operations. The extra time is due to the way the physical layer and link layer are communicating. Only after a full decoupling sequence, a rotation gate can be performed. This means that if the link layer wants to do more rotation gates, it only sends them after receiving the outcome success of the previous gate. This means that between each gate, there must be at least one decoupling sequence of $\approx 180\mu$s. The same applies between the last rotation gate and the execution of the measurement.

7.1.3 Control over memory qubits

In the past, it is shown that with the addition of one or more memory qubits to the network nodes, more quantum network experiments can be done. These are sending a qubit via teleportation and entanglement swapping for the network layer [6]. While control over multiple memory qubits for a single node has been demonstrated [26], they're not yet integrated in the used physical layer.

The quantum nodes used in this research contain more than just communication qubits (the NV centres). In the diamond lattices, there are some carbon-13 atoms in the environment near the position of the NV centre. This ^{13}C atoms are not only influencing the magnetic field around the NV, but can also be used as memory qubits. In previous research, done with the same quantum nodes, they were able to control the memory qubit and use it to generate entanglement between two non-neighbouring nodes [5]. This means it is possible to use the ^{13}C atoms as memory qubits in the used setup. Gaining real-time control over these memory qubits via the link layer is planned to be achieved in the near future.

7.1.4 BQC tests

The main objective of this research is to demonstrate the operation of the physical layer and link layer. When that works, follow-up research can be carried out into the upper layers in the quantum network stack. One of the applications that can be used to showcase the quantum network stack is to perform a Blind Quantum Computation (BQC) [21]. BQC means that, instead of using only your own quantum computing device, calculations can be outsourced to quantum servers that do the work for you. The term "blind" refers to the fact that quantum servers do not have full knowledge of the tasks they are calculating, so the clients' computing tasks remain secure.

The remote state preparation test done in this research comes in handy when it is possible to perform computations on a remote quantum server. The client is allowed to prepare a state remotely and keep the computations performed private while running quantum applications on a powerful quantum server using all the qubits the server has.

By expanding the remote state preparation protocol and add control over the memory qubits, the setups becomes close to ready to perform full Blind Quantum Computation. Next, the two-qubit gates like a CNot gate needs to be implemented. The full BQC test consist of a combination of remote state preparation and control of the memory qubit, among others for showing remote preparation of two qubits while keeping the first one alive in the server.

Part III

Communication Design for Innovation

Chapter 8

Introduction

8.1 Introduction on quantum

Quantum technology is an emerging technology of the 21st century with the potential to transform society and industry [27], but understanding quantum is also difficult, even Einstein thought it was 'spooky action' [28]. Explaining it proves to be tough, since quantum mechanics is basically a mathematical theory that is now moving into a physical application. As Richard Feynman, a pioneer of quantum computing, once said of his Nobel Prize-winning work on quantum electrodynamics: "if it were possible to describe it in a few sentences, it wouldn't have been worth a Nobel Prize." [29]. Although it is difficult to understand exactly how it works, it has a lot of potential. Quantum technology uses the special behaviour of the very smallest particles to calculate, communicate and measure in a radically new way. Quantum computers, networks, and sensors have a broad spectrum of applications, including for the climate, energy-efficient food production, new materials, medicines, optimization issues in machine learning and cybersecurity. Quantum technology is still in a relatively early phase: the first "low-hanging fruit" applications are now coming onto the market, but the groundbreaking applications are still in the R&D phase.

Lawrence Gasman, founder of Inside Quantum Technology, first heard the idea of quantum computers when he was at a conference about new directions for quantum, new directions for computing, around 30 years ago. Gasman: "Quantum has been discussed in a lot of very technical conferences on quantum information science. Only in the last five or six years, products did emerge." Building a quantum computer is a big challenge, so more people need to be involved in the process of building one. As with all technological developments, it will only get faster, just as computing power will just get faster based on Moore's law.

The promise of quantum technology is so great that countries around the world are trying to be the first to develop it to a usable stage. Due to the high potential and strategic nature, investments are needed to start booming to stay ahead in the technological world. Universities can not do this on their own, since they lack the knowledge of what is needed and wanted in industry, so they start collaborating to be in the lead of the development.

This means that the development of quantum technologies is relatively new, and that there is still much to be discovered. Although the uncertainty of what is not known yet is clear, there are also a number of potential applications of quantum. This friction surface of the uncertainty of what will work and what will not, and the high expectations of applications, makes the development of quantum technologies an interesting field to discover. These high expectations are often called the quantum hype. This hype has been generated by breakthroughs in the past decade, which have shown that quantum mechanical principles can be applied in groundbreaking new technologies. The radical new applications based on quantum technology offer promising opportunities for industry and can help find solutions to some of society's biggest challenges [30].

In Delft, the university formed a collaboration with research institute TNO to form a combined research organization focused on quantum computing, quantum internet and qubit research, called QuTech [31]. This collaboration is having success in the development of quantum technologies, with multiple papers in reputable journals like Science and Nature, and they started working together with more parties [32, 33].

Within the Netherlands, QuTech is collaborating with other universities and research institutes, but also spin-off start-ups of the university and bigger companies in the Netherlands. Together they form Quantum Delta NL, an 'ecosystem for excellence in quantum innovation'. Their aim is to develop and apply quantum technology in innovative ways. To do that, key scientific and technological difficulties must be overcome and several technologies and disciplines need to be combined. By working together, they want to improve technology readiness levels across the board [34].

Quantum Delta NL just gained a large funding for developing and exploiting quantum technology and stay a frontrunner in the quantum field [35, 36]. Besides doing research in quantum networking, quantum computing, quantum internet and more, the funding is also meant to involve companies into the quantum development. These companies are needed to lay a base for a new high-tech sector in the Netherlands, which creates value and jobs. Quantum Delta NL believes that quantum technology which will have a major impact on the economy and society, from the development of new materials and medicines, to making chemical processes energy efficient, to making data communication unbreakable [34, 35].

The fact that so much is already being invested by companies and governments in a technology that is actually still in its infancy is extraordinary, Kees Eijkel, Director of Business Development at QuTech, believes: “Because normally the big companies give you the run-around when they start making the big money, this does not apply to quantum. Because the winning technology stack has not yet been defined at all.”

Dan Howell, Operational Lead of the Quantum Delft ecosystem, states that the applicability of quantum will all depend on how the technology develops and how we can get the applications working. He says: “I think it is important that everyone is aware of the concept of what quantum technology can potentially mean for different industries, because the implications are potentially huge.” What they agree on is that quantum technology was first in the scientific phase, but it is now starting to become applicable in industry.

With any new technology, it is important to engage societal actors in an early stage of the technology's development [37, 38]. For quantum technology, these actors include business organizations and government institutions. There are three main reasons to get them involved. The first reason is that more stakeholders provide a broader perspective on the issue. This could lead to more socially resilient solutions [39]. In addition, more support and less public opposition can be gained by involving society [40]. Finally, stakeholders outside quantum research should be able to express their ideas and concerns about changes that have a significant impact on their lives from a democratic perspective [38]. Section 10.6 provides insight into whom these stakeholders are and what impact quantum technology can have on their business.

8.2 Directions in quantum technologies

Although the first applications of quantum technology in industry are starting to become applicable, we are not yet close to a fully-fledged quantum computer. There is still a lot of fundamental R&D work to be done in the field of quantum, so-called fundamental science. This is expected to be done at universities alone or in collaboration with industry.

These new applications of quantum technology can be found in three main directions: quantum computing, quantum networks and quantum sensing. Each direction is different in its development. For example, quantum computers have the potential to solve certain problems much faster than 'classical' computers ever can, and quantum simulation gives us the means to help unravel quantum processes, such as the complex behaviour of molecules. Communication via quantum networks makes it possible to solve certain distributed problems more efficiently and to communicate securely, with little or no interception of messages – if someone tries to intercept, both sender and receiver will know immediately. And with quantum sensors, highly sensitive measurements can be made on a very small scale, in ways that are impossible with classical sensors.

Jesse Robbers, Director Industry & Digital Infrastructure at Quantum Delta NL, puts it as follows: “I think the heart beats for quantum computing, quantum networks and quantum sensing are different. They all have their own heart beats when it comes to making technology tangible.” What he means by this is that the technologies are at different stages of development. For example, the first quantum sensors are already available, while a real working quantum computer is still a dream for the future. Although there are three areas of quantum technologies, which are not at the same point of development in time, the way they collaboratively work on it remains the same. In the rest of the thesis, therefore, the development of quantum technology relates to all three areas, except where it is explicitly stated that it applies to only one of them.

8.3 Quantum acceptation

Despite the fact that quantum technologies hold great promises, there is still a lot of work to be done to convince the industry to embrace them. Kees Eijkel compares it to the digital transformation that took place 20 years ago: “With quantum, it is the same story, and that has not even to do with acceptance but with expertise.” Also, Ingrid Romijn, Program Manager at QuTech, sees this gap between universities and industry: “What I always try to do with companies is that, on the one hand, it is very good to read up, go to lectures, look at the websites and talk to people at a high level. But, a project where you really start looking at what can it do for me? Can we think of something concrete yet? That is the best way for companies to get involved.”

To gain acceptance of quantum technologies, several things need to happen for companies to get involved. Lawrence Gasman gives an example for the financial sector: “If we talk about financial services, there are two aspects to their reluctance to jump into quantum. One is that there are not enough qubits to do something that you could not do in any other way. But also, if you are talking specifically about financial services, trust has to be built. It is nice to know you can use quantum computing to optimize an important portfolio, but you would better be as confident as you can be that you can actually do it, otherwise your wealthy clients who just spent a billion dollars would not be happy.” The lack of applicability of the technology and the lack of confidence in the technology is a major hurdle that must be overcome to fully engage the industry.

One way to overcome this hurdle, according to Jesse Robbers, is to take companies by the hand and show them what is possible. To do that, different people in the company need to be open to change, and understand the importance of quantum technologies in the future. So if they want to make use of them in the future, they have to start building up knowledge of them now. This can be applied in commercial products and services. If the company does not have to do this all by itself, but is guided in this process, it is more likely to be open and ready for it.

8.4 Introduction of research project

In the field of quantum technology, much research and development work is currently being carried out at universities. This has its origins in the fact that the theory of quantum mechanics is now being tried out in the laboratories before it can be put into practice. This research into a new technology promises much if it is made possible, but if the industry is not involved in the development, a so-called technology push situation arises.

The technology-push approach emphasizes the importance of science and technology in producing technological innovations, as well as adapting to changing industry structure characteristics [41]. Opposed to the technology-push effect is the demand-pull, or market-pull, effect, which means that when the market demands a certain type of product (or service), or when a problem is identified, producers respond by producing and supplying it [42]. In the paper by Mowery & Rosenberg, they argue that both the push and pull effect are important in the development of innovative technologies [43].

This technology push from universities, when they develop technological innovations on their own, to industry is not desirable. There must also be a demand from industry for universities to create the pull effect. In order to achieve the optimal balance between push and pull, universities and industries must work together. Therefore, the focus of the thesis will be on university-industry collaborations in the development of quantum technologies.

Collaboration is a very broad concept and can include many forms of interaction. If we look at the definition of collaboration, it says: 'the situation in which two or more people work together to create or achieve the same thing' [44]. This definition was chosen because in the field of quantum technology, the aim is to make the theory work in practice and when that is achieved, to take it out of the lab and use it in industry. This definition will be used throughout the thesis when talking about collaboration, where in this case the desire is to work together to create new quantum technologies.

The problem is that setting up a collaboration to work on something new is quite difficult. This is also the reason why research is currently mainly carried out at universities, whereas industry is only starting to look around at what is going on. In order to achieve this balance between technology push and market pull for creating innovations, industry needs to be more involved in the development of quantum technologies.

To understand collaborations in general and what is going on in the field of quantum, one has to delve into the literature, as well as conversations with people in the field. Since most people involved in quantum work at universities, the research will be conducted from a university perspective. This means that the main focus will be on how universities can convince industry to get involved, although at the same time, the barriers of universities in this process need to be analysed. This will form the basis for the research carried out in the thesis.

8.5 Entanglement in collaboration

One of the two main theories in quantum mechanics is that of entanglement. Entanglement is a phenomenon where the state of a particle is inseparable from the state of another particle. This means that if one measures and knows the state of the first particle, the state of the second particle is also known without measuring it. This happens on a very small scale of particles. It is difficult to achieve entanglement, see Part II of this thesis, but when it is induced the connection is very reliable.

To draw a comparison with university-industry collaboration, that is also difficult to achieve. For two particles to entangle with each other, they must have the same wavelength. A change in wavelength of one of the two, interrupts the generation of entanglement and no connection is made. This principle also applies to universities and industry. They have to find a common wavelength in order to establish collaboration. Both start with different starting points, but they must find common ground to build collaboration and form an 'entangled pair' that is successful.

Finding this common ground is not so easy. Both parties are influenced by their environment, but they also differ internally. They have different goals, different ways of working and different circumstances at play. Just like generating 'real physical' entanglement, a lot of communication is needed. Back-and-forth communication between the two parties is needed to find places where they can come closer together, and where they can be on the same wavelength to build collaboration.

The analogy of entanglement may not be quite right physically, because when they enter into a collaboration, you cannot 'measure' one, and you do not exactly know what state the other is in. But it shows the importance of communication and being on the same page before it is possible to entangle with another party and be successful with that collaboration.

8.6 Research questions

The main gain from this project is to create a vision of how the collaboration between companies and universities in the quantum technology should look like. This is necessary to get the collaboration between universities and companies going, to be able to lay a base for a new high-tech sector in the Netherlands, which creates value and jobs. This is done with the belief that quantum technology will have a major impact on the economy and society [35]. Therefore, the main research question is:

What should be the vision for collaboration between industry and universities in the development of quantum technology?

The goal is to investigate the possibilities of involving companies in quantum technology. Firstly, a detailed overview of all stakeholders in university-industry collaborations is established. Secondly, it looks at the reasons for companies to collaborate with universities, to see what the point of doing so is for them. Further, when the reasons to collaborate are clear, examine how and in which way they can best collaborate in the field of quantum technology. With the stakeholders, purpose and type of collaboration known, the factors that influence the collaboration positively and negatively are discussed. When all aspects are clear, a vision on how the collaboration between companies and universities in the quantum technology should look like can be made. Therefore, the sub-questions are:

1. Who are the stakeholders in the development of quantum technology?
2. What should be the purpose of collaboration between universities and industry in the quantum technology?
3. Which type of collaboration is most suitable for quantum technology development?
4. Which factors are influencing the collaborations?
5. What are the next steps in creating collaborations between universities and industry in the development of quantum technology?

One of the parts of the research portfolio of CDI group is to use communication-based solutions in which education, research and business are connected to speed up the innovation processes and their outcomes today and in the future [45]. In order to realize this, research to transdisciplinary collaborations is executed. The underlying idea of my research is to create more and more collaboration between industry and universities. The collaboration between business and academia can boost the development of quantum technologies and add value to the economy. Working together makes growth of knowledge, high specialization of scientific domains and quickly changing technology possible. The scientific problems to be solved are complex in nature, as are the social aspects of these challenges.

Chapter 9

Methods

To find the answers to the sub-questions and the main question, different methods are used. The most important methods used for this research are a narrative literature review and semi-structured interviews with those involved in the field. Both information found in literature articles and the findings of the interviews are used to come to answers to the first four sub-questions.

First, a narrative literature review is done and later the literature associated with each sub-question is explored in more detail. The literature review is done first to get an idea of the answer to each sub-question. The literature is searched for theories and methods, which form the theoretical basis to find an answer to each sub-question.

After this literature review and establishing a theoretical basis, interviews could be conducted with people in the field of quantum. In the interviews, the questions were constructed so that the conversations were about an answer to the same sub-questions. The interviews sometimes gave a broader picture of what was going on in the field, but mostly they gave a more detailed picture of how the theoretical basis worked in practice. These interviews enriched the knowledge of the situation in the field.

The results of the literature review and the findings of the interviews were combined to get a substantiated answer to each of the first four sub-questions. In combining all these arguments, it turned out that some only appeared in the literature, while others only emerged during the interviews. Based on this, a good picture could be formed of what is relevant in the field of the development of quantum technology. From this picture, conclusions could be drawn for each of the first four sub-questions.

With all the input obtained from the other sub-questions, a vision on collaboration between companies and institutions in the development of quantum technologies has been developed. So by using the information about, the purpose of collaboration, the type of collaboration and the positive and negative influence factors, a vision can be created. This vision contains how to work together to achieve the goals of a fruitful collaboration. Figure 9.1 shows the design of the research carried out.

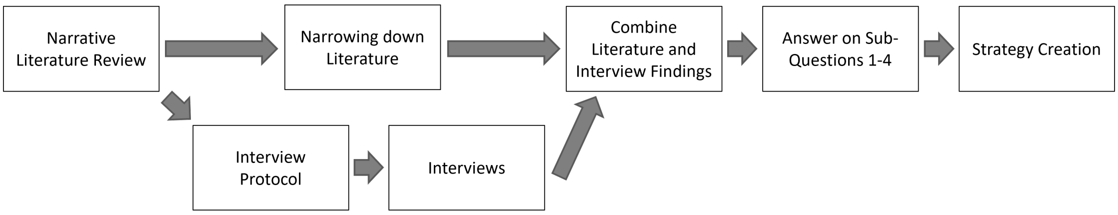


Figure 9.1: ***Schematic overview research approach.*** *First, a picture of the current situation is obtained. A narrative literature review is used to find more in-depth literature, while the interview protocols are also drawn up. The results of the literature and the interviews are combined to find answers to the first four sub-questions. From here, a vision can be developed.*

9.1 Narrative literature review

Before delving deep into the literature to answer the sub-questions, the first step is to become familiar with the context of the development of quantum technology. In order to gain insight into the current situation, such as what is the history of quantum, what has already been done, what is happening now, etc. To this end, a narrative literature review is be conducted to gain insight into the current knowledge on university-industry collaborations and how to collaborate in general. The goal of the narrative review is to get a basic understanding of the subject area.

The narrative literature review has an explorative character, which means it is not well-structured. Therefore, the process is more alike to convenience and snowball sampling. With convenience is meant, the first available and accessible articles for the researcher are sampled. Finding an interesting article with multiple citations, and continue reading the articles of these citations, is called snowballing. So using the easy to grasp information and use the reviewed sources as new source is the main method used for the narrative literature review. This is an iterative process, which in the end result in an overview of the related articles to the topic.

To find the first information and articles, Scopus was used as a source. The initial search terms for the narrative literature review are based on obtaining information about collaboration in general and the quantum situation. They include: 'co-creation', 'collaboration motivation', 'university-industry collaboration', 'collaboration readiness', 'collaborative network organisations', 'interdisciplinary collaboration', 'innovation collaboration' and 'quantum collaboration'. Some search terms gave a lot of useful articles, while others did not give back relevant articles for this research. The literature was chosen based on the title, the abstract's overall impression and the number of citations. New articles were also discovered in the found literature. Besides theses of other CDI master students were used to gain inside in the procedure of doing literature review and tips to find more relevant literature.

Table 9.1: ***Narrative literature overview.*** *All articles found in the narrative literature review are group per theme. These themes are chosen based on (parts of) sub-questions.*

Theme of the article	**Reference**
Co-creation	Galvagno & Dalli, 2014 [46]; Kirstensson et al., 2008 [47]; Biggs & Smith, 1998 [48]; Batenburg & Rutten, 2003 [49]; Peña, 2002 [50]; Sonnenwald, 2007 [51]
University-Industry Collaboration	Hayter et al., 2018 [52]; Alpaydin, 2021 [53]; Rajalo & Vadi, 2017 [54]; Petricevic & Verbeke, 2019 [55]; Jackson et al., 2017 [56]; Sjöö & Hellström, 2019 [57]; He et al., 2021 [58]; Perkmann & Walsh, 2007 [59]; Perkmann et al., 2019 [60]; Bekkers & Bodas Freitas, 2008 [61]; de Fuentes & Dutrénit, 2012 [62]; Guan & Zhao, 2013 [63]; Lee, 1996 [64]; Siegel et al., 2003 [65]; Bruneel et al., 2010 [66]; Gochermann & Bense, 2004 [67]; Nielsen & Cappelen, 2014 [68]; Bikard et al., 2016 [69]; Perkmann et al., 2013 [70]; Huhtelin & Nenonen, 2015 [71]
Collaboration Readiness	Balasubramanian et al., 2021 [72]; Romero et al., 2009 [73]; Davis, 1989 [74]; Lin et al., 2007 [75]; Parasuraman, 2000 [76]; Lotrecchiano et al., 2016 [77]; Blomqvist et al., 2005 [78]; Durugbo, 2015 [79]; Romero et al., 2008 [80]; Rosas & Camarinha-Matos, 2009 [81]
Quantum Development	Forbes et al., 2021 [82]; Wehner et al., 2018 [27]; Kim et al., 2021 [83]; Chicago Quantum, 2020 [84]; Peterssen, 2020 [85]; Srivastava et al., 2016 [86]; Inglesant et al., 2016 [87]

Not all the literature found was about the same subject. The articles found using search terms such as 'co-creation' provided different information than the articles found using terms such as 'collaboration motivation', 'university-industry collaboration', 'collaborative network organisations' and 'interdisciplinary collaboration'. In order to create an overview of all the information, the articles were grouped by theme. These themes have been chosen so that each theme can be used for different (parts of) sub-questions.

All articles on co-creation have been grouped under the theme *Co-creation*. The articles that contain information on *University-Industry Collaboration* can be used for the sub-questions on the purpose, type and stakeholder of the collaboration. The article belonging to the theme of *Collaboration Readiness* can be used when looking at the current situation and how it will develop in the coming years. In order to get a better overview of the current state of affairs in the field of quantum development, some articles with a vision of the quantum future are also included in the theme *Quantum Development*. An overview of the literature found in combination with the theme of the article can be found in Table 9.1.

Aspects of University-Industry Collaborations

Much research has already been done on the topic of cooperation and co-creation. When looking more closely at the cooperation between universities and business, various aspects are discussed in the articles. When reviewing the literature, it appears that several articles have been written about the same aspects. By delving deeper into these articles and noting down the main themes, an overview could be made of the most common issues discussed in the literature. By grouping the main themes, five most common aspects could be distilled. For example, themes that are grouped are enablers [57], driving forces [62] and benefits [68]. All these articles contain information around the aspect of 'drivers'. The other aspects are:

- **Goal**: the intention with which the collaboration is set up.
- **Manner**: the way in which the collaboration is implemented/formed.
- **Context**: environmental factors that play a role in the collaboration.
- **Driver**: factor that positively influences the creation or realization of collaboration.
- **Barrier**: factor that negatively influences the creation or realization of collaboration.

These aspects are in line with the structure of the sub-questions. The goal of the collaboration is the objective on which the collaboration is created. This goal can also be called the purpose of the collaboration, and possible purposes are set out in Chapter 11. The manner of collaboration is part of sub-question three, which deals with the type of collaboration. When determining the type of collaboration, the aspect of context must also be taken into account. These two aspects are therefore discussed in more detail in Chapter 12. The drivers and barriers to collaboration are influencing factors. Many different arguments can be found in the literature, and in Chapter 13 these arguments are compared with those that emerged in the interviews, to find out which ones are applicable in the field of quantum development.

For the first four sub-questions, the literature is used to find the ideas, theories and discussions which exist about these aspects. This is done in a snowballing way, by going through the sources of the articles found in the narrative literature search, to look for new articles that could be relevant for answering (one of) the sub-questions. Whereas in the search for the current situation only the title and the summary were looked at, now more of the articles were read. This started with reading the summary and deciding which part of the article might be interesting. This could be the whole article, or only certain parts of it. The interesting parts were read, and the main conclusions were written down. With these main points, they could be sorted by sub-question. Some articles had the same arguments, while others had contradictory arguments. These were compiled, and the result can be found in the chapter of each sub-question.

9.2 Interviews

9.2.1 Interview protocol

In addition to literature research, semi-structured interviews are conducted with people involved in the development of quantum technologies. A semi-structured interview protocol was used for the interviews to try to get all interviewees to shed light on the current situation of quantum development, the collaborations between universities and industry in the field of quantum – what is happening now and what do you want them to look like – and the readiness of those involved. To make the protocol such, that in all interviews each concept of all first four sub-questions are discussed, the questions were grouped per concept. This overview can be found in Table 9.2.

Each interview started with an introduction of myself and the idea behind the research, followed by an introduction of the interviewee itself. This introduction was used to place the answers in the perspective of the interviewee's field of work. Based on what they had said in their introduction, the questions were asked concept by concept. An effort was made to follow the order of the concepts most of the time, but if the interviewee had already touched on a concept, that concept was discussed first before the others. Therefore, not all questions were asked exactly as prepared and not in the same order, due to the flow of the conversation and the answers already given.

During the interviews, several examples of relationships and companies came to light, some of which are not yet intended for public consumption. Those names or passages have therefore been omitted from the transcriptions.

Table 9.2: ***Interview protocol.*** *Based on the structure of the sub-questions, six categories could be distinguished. Each category is divided into the concepts that belong to that category. For each concept, interview questions were devised to get a clear picture of the interviewee's opinion on that concept.*

Category	**Concept**	**Interview questions**
Background	Personal introduction	• Can you give an introduction about yourself?
	Quantum	• What is your relation to quantum? • What do you expect to happen in the development of quantum technology in the coming years?
Stakeholders	General	• Who should be involved in the development of quantum technology? • Who are already involved?
	Industry	• Which type of companies from industry are needed to be involved? • Are there specific companies you want to that become involved that are not there yet?
Purpose	Needs	• What knowledge do you need from [industry/universities] in a collaboration?
	Purpose	• What do you think should be the main purpose for universities to collaborate with industry? And vice versa?
Type	Expectations	• What do you expect from the other party in the interaction? - How should they become involved? - How should this collaboration look like? - Which form should the collaboration take?
Influences	Positive	• What do you see as the main benefits for [industry/university] to collaborate with [university/industry]?
	Negative	• What are the barriers for those collaborations? • And what are the risks?
Future	Collaboration readiness	• Is the university ready to collaborate with industry? - Why or why not? - If not, what should happen to make them ready? • Is the industry/are the companies ready to collaborate with the universities? - Why or why not? - If not, what should happen to make them ready?

9.2.2 Interviewees

To gain more insight into the current state of the art in quantum development, five interviews were held with people from different fields within quantum development. Network connections are used to get in touch with the people for interviews, and recommendations from the first responders to other people are also used. They have different roles in the field of quantum, some at QuTech and others in larger quantum ecosystems. This makes that they all have a different relationship to the quantum field. They are not academic researchers, but they work on partnerships and ecosystems in the field of quantum. They do so at university level, regional level and national level. With each of them, different aspects of the current state of the field, their views on the collaborations and visions for the future are discussed. For the purposes of this thesis, all interviewees provided their consent to have their names and the topics covered during the interview made public.

Since four of the five interviews were done with people involved in development in the Netherlands, while there is also some insight into what is happening in the rest of Europe, the focus of the research will be on what collaboration looks like in the Netherlands. The results are most likely applicable in the rest of Europe, but will not work outside Europe, due to the different visions on the development of quantum technology. This will become clearer in the course of the report.

The first person spoken to is Kees Eijkel, Director of Business Development at QuTech, which means that his daily job is to find external parties to collaborate with. He wants these collaborations to be able to get to their mission, which is to create scalable prototypes. In his own words: 'That are things that work with a system and everything that is attached to it and that you, as a user, can access.' In QuTech a lot of academic research is done, and those scalable prototypes are additional to the normal academic setting.

Lawrence Gasman is the second person spoken to. He is from the US and is a bit of an outlier, since he is not working on collaborations inside quantum. He is the founder of Inside Quantum Technology, a company that provides access to insider knowledge from company insiders, government officials, and academic groups. IQT hosts a number of international conferences and exhibitions, as well as IQT research and consultancy.

The third interview was with Dan Howell, the Operational Lead of the Quantum Delft ecosystem. Quantum Delft is the ecosystem of a fast increasing community of quantum technology researchers, startups, and established corporations. In the quantum technologies, they are all trying to be at the forefront. He is also the director of the Delftechpark's new House of Quantum. This is the physical center of the Quantum Delft and Quantum Delta NL ecosystems, and it is an inspirational community facility that fosters interaction between disciplines and domains, as well as being home to quantum start-up and scale-up businesses.

Next, Jesse Robbers works on the collaborations on a national level. He is Director Industry & Digital Infrastructure at Quantum Delta NL. Quantum Delta NL is building a national ecosystem for quantum innovation, attracting highly skilled professionals to develop quantum computers, quantum networks and quantum sensors. His motivation is to make new technology also applicable on the industrial side. And by coming from the industry side, he is able to bridge (complex) customer and market developments to new opportunities, build new business models, products and/or partnerships and translate new technical possibilities into new solutions.

The last interview was with Ingrid Romijn, Program Manager at QuTech. Her responsibilities include project development, technology transfer, and quantum technology industrialization. She works to bring quantum technology from the laboratory and academic research environment into society, while also acquiring new initiatives and protecting intellectual property. Ingrid was also a member of the team that designed and produced the Dutch National Agenda for Quantum Technology.

9.2.3 Interview coding

The interviews were recorded and transcribed afterwards. The rough transcription was done with the dictation function of Word, after which the rough text was corrected and completed by hand. These transcripts were then qualitatively coded. This is a process of systematically categorising fragments of qualitative data to find themes and patterns. It allows semi-structured transcripts of interviews to be taken and structured into themes and patterns for analysis. Coding the qualitative data makes the analysis more systematic.

The elements used for coding are divided into groups, based on the main sub-question to which they belong. These groups of coding elements can be found in Table 9.3. In each interview, quotes belonging to one or more elements were coded and collected from all interviews for each element. All the elements belonging to the same sub-question are worked out in the chapters of each sub-question.

Table 9.3: ***Interview coding elements of this research.*** *The elements used for coding are divided into groups, based on the main sub-question to which they belong. In each interview, all quotes belonging to one or more elements were coded and collected from all interviews for each element.*

Coding element	**Sub-question**
Background	-
Current status	-
Location	-
Stakeholders	1
Type of company	1
Company already involved	1
Potential company	1
Purpose collaboration	2
Motivation	2
Funding	2
Type of collaboration	3
Expectations	3
Advantage collaboration	4
Driver collaboration	4
Risk collaboration	4
Barrier collaboration	4
Readiness	5
Initiatives	5
Vision on future	5

Chapter 10

Stakeholders

According to the main research question, universities, and industry should be involved in this collaboration of quantum development. In this part, the focus is on whom the stakeholders exactly are in these collaborations.

A stakeholder is an individual or group of individuals who can influence or be influenced by a project. Individuals working on a project, groups of people or organizations, or even sectors of the population can all be considered stakeholders. A stakeholder can be actively participating in a project's work, affected by its conclusion, or in a position to influence its success. Stakeholders might be inside or external to a project's organization. It is essential to recognize that not all stakeholders will have the same impact or influence on a project, nor will they be affected in the same way.

In the interviews, the interviewees discussed the stakeholders involved in the collaboration between universities and industry, as well as the sectors they expect to be involved in first. An overview was also given of the sectors and what role they might play in the development of quantum technologies.

10.1 University

Let's start with the universities. Universities are part of the higher-education system. A university is an institution of higher education that is designed to provide scientific education and conduct scientific research. Both these two parts are important in the development of quantum.

On one hand, the scientific education part of the universities is very important in the training of students to become the future researchers in the field of quantum. This training can be done in a specific bachelor or masters programme, focussing on quantum development. For example, at the Delft University of Technology they are working on a new master's programme, the Quantum Information Science & Technology (QIST). In this new master's programme, the curriculum will be interdisciplinary and consist of physics, mathematics, electrical engineering and computer science [88]. Their reason for starting a specific master's programme on quantum: "McKinsey and TNO expect that the field of quantum technology will grow enormously". This means that many more people with specific knowledge are needed to allow the field to grow. As an illustration of the growth, the Ministry of Economic Affairs and Climate Change's commitment of EUR 615 million to the Quantum Delta NL programme to stimulate quantum technology in the Netherlands by 2021 is cited [36]. To cope with the growth and development of quantum devices, the TU believes it is necessary to train multidisciplinary engineers with a background in electronics, computer science and mathematics, in addition to quantum physics skills.

In addition to education in a specific discipline with an emphasis on quantum, other students also receive education on quantum. Courses in (applied) physics, computer science, chemistry, mathematics, biology and material sciences include courses on quantum. These range from the basic physical theories in quantum mechanics to how quantum can be applied in a specific field. In mathematics or computer science, for example, a quantum course may deal with quantum algorithms, and in chemistry or materials science with the quantum properties of materials and how this affects a system. By not only involving students who have chosen a specific quantum programme, but also educating a wider range of students with the basics of quantum mechanics, more graduate students can enter the field of quantum development. This should be done more and more to meet the demand for researchers as the field grows rapidly.

Next to its educational function, a university also has a research function. Today, research in the field of quantum is still mainly carried out in the laboratories of universities. Professors, post-docs, PhD students and technical staff work together to lead the way and make new discoveries in the field of quantum. In the Netherlands, universities and knowledge institutes have a leading position in the worldwide development of quantum hardware and software and the associated control algorithms and applications. They are a frontrunner in the field of qubits, quantum internet, quantum algorithms and post-quantum cryptography [30]. The development of quantum computers, quantum communication systems, quantum sensors and quantum simulators has the potential to help solve societal challenges and offers opportunities to all sectors of the economy. Although concrete applications of the technology are already being used, much development is still required before we can have, for example, a fully-fledged quantum Internet or a large, universal quantum computer.

To be able to perform the research into quantum technology, multiple things are needed. The first one is good people, as already mentioned earlier. Next is a plan, so timelines have to be made for the short term as in the long term. These plans should contain all different aspects of the quantum field, so for each now thought of technology should have a plan for the future. The future is not only where the technology should be in 20-30 years, but also steps in between. So, what should be done in the next 5 years, the 5 years after and over 10 years. Last, to be able to execute this plans with the right people, money is needed. Investments need to be made in the technology, to be able to do more research and stay in the front at quantum development.

There are different ways for universities to get money for their research. In the Netherlands, there are three main ways of getting money [89]: The first money flow comes from the government funding. This contribution constitutes the largest part of the financing of the basic infrastructure of each university: salaries of lecturers and researchers, supporting staff and staff, buildings, laboratories, and libraries. With the government's contribution, a university carries out its statutory tasks in the area of academic education and research, as well as valorization. The government's contribution consists of four parts, namely the education part, the research part and the medical education and research part. Although this first money flow is quite big, it is not only meant for research but also a lot of different other things that need to be paid.

The second money flow comes from the NWO. The Netherlands Organization for Scientific Research (NWO) ensures quality and innovation in science and is one of the most important science funders in the Netherlands. Each year NWO invests nearly 1 billion euros in curiosity-driven research, research focused on societal challenges and research infrastructure. On the basis of advice from expert scientists and experts from the Netherlands and abroad, NWO selects and funds research proposals. NWO encourages national and international collaboration, invests in large research facilities and promotes knowledge utilization. NWO funds just over 7000 research projects at universities and other knowledge institutions [90].

The third flow of money consists of other income, such as funds from the EU, contract teaching or research and collection box funds. Dutch universities receive a larger share of their income through research for governments, companies and non-profit organisations than they did a decade ago. The growth in this category is mainly due to the fact that universities are increasingly receiving project grants from Europe (European Framework Programme for Research and Innovation). For quantum, this grant come from the 'Quantum Flagship' programme of the EU [91].

Next to the money coming from governements, NWO and EU, money becomes also available via large companies and venture capital. “The amount of money that is put into the field by venture capital in the US is enormous, so much money goes into it. And in Europe we are lagging behind quite a bit,” both Dan Howell and Ingrid Romijn state this. Jesse Robbers adds: “More and more venture capital is becoming available to invest in this. Parties such as PsyQuantum are enormously large companies that are, of course, also overvalued, where very large flows of money have become available to ultimately further develop quantum technology in such a company. That means that you have to hook into them, that you will get a flywheel effect in the development."

These flows of money automatically result in the government, NWO, EU and companies to also be stakeholders in the development of quantum technologies.

10.2 Government

The government is supporting each university in the Netherlands with money. This money is meant for both educational and research purposes. The part that is used to finance the basic facilities for scientific research is called the research part. Whereas the education component of this funding grows along with the number of students, the research component has been stable for quite some time. This component is distributed on the basis of the number of diplomas and PhDs and a portion of core funding. Given the fact that education and research are intertwined, the fact that the research component of funding does not grow with the number of students is an important explanation why universities have come under increasing financial pressure in recent years, with a very strong growth in the number of students [92].

How the research money is distributed among the faculties is decided by the universities themselves. The government does not decide which research project the money goes to. For the funding of the development of quantum technology, this means that some money comes from the government, but there is no guarantee that the university itself will invest this money in quantum and not in another technology. So all the money that comes from the government helps, but there must be more stable sources of money to do the development.

Besides the money every university gets from the government, they also have money available for other special initiatives in research. The Dutch Ministry of Economic Affairs and Climate Policy announced a €615 million investment in quantum technology advancement. The consortium Quantum Delta Nederland just gained a large funding for developing and exploiting quantum technology and stay a frontrunner in the quantum field [35].

The reason for governments to invest in quantum is the potential that the technology can offer society. The money usually comes to the universities to do fundamental research. At the same time, spin-off companies from universities start businesses using the knowledge they have gained from the universities to make a commercial product that can be used in society. This brings us to a dilemma, according to Dan Howell: "It comes down to the concept of government-funded research, like taxpayers' money going into research. So to then make a business out of the result of that research and commercialize it is a bit of a tricky area. Because you are building on all that taxpayers' money, and so there is a kind of moral dilemma. Should universities let the IP go and let the business flourish? Or should they keep some sort of grip on it and stifle the whole thing? Either way, it is a tricky situation. It also has to do with national state aid, the kind of state aid to companies that cannot use public money. And so that is another area that people are quite afraid of, because they do not want to use public money for commercial business advantage. So that puts people off, but it is important to support these companies with facilities and with that, and as long as you do it in the right way and the transparent way, it is really valuable."

The government's influence on quantum technologies is mainly in the funding of research in the field of quantum technologies [36]. While this really helps the scientific community and also promotes partnerships between universities and industry, the government itself is not yet participating in quantum developments. According to Jesse Robbers, this needs to change soon: "We think that the first generation of quantum network technologies helps to secure data. Securing data is very crucial in the government domain. Think about personal data and state security, which are very information intensive. So at a very early stage, you actually want to involve various parties who exchange data in the government domain."

10.3 NWO

The Netherlands Organization for Scientific Research (NWO) is one of the most important science funders in the Netherlands. NWO receives public money for science from the Ministry of Education, Culture and Science and many other ministries, which is distributed in competition among the universities and national research institutes. NWO manages this funding stream and ensures that the money gets to the best scientific talent and the best research proposals. Through NWO, industry and social organisations also contribute to financial support for research in their field, typically in the form of jointly funded thematic programmes.

The NWO divides the money on the basis of advice from expert scientists and experts from the Netherlands and abroad and based on their strategic plan called 'Connecting science and society'. NWO emphasizes its connecting role: together with its knowledge partners, it connects people within science and between science and society [93]. This plan consists of five ambitions, on the basis of which decisions are made. The most important ambitions for the quantum development in collaboration between universities and industry are: Nexus – Linking Agendas, Science and Society, Research – Collaboration for Excellence and Renewal, and Knowledge Utilization – Effective Use of Knowledge through Co-Design and Co-Creation.

They themselves say the following about the ambition 'Linking Agendas, Science and Society, Research': NWO wants to provide more coordination and direction in Dutch science so that a national research strategy can be developed including a regularly updated National Science Agenda (NWA). Programmes in the NWA are set up from the perspective of the breadth of science and offer room for a broad chain approach in which, where relevant, fundamental, strategic, practice-oriented and applied research are linked. Non-scientific parties can also be involved in the execution of research in these programmes.

For quantum, a National Agenda for Quantum Technology has been set up in early 2020. This document sets out the agenda for taking up the challenge together in the Netherlands and investing in new talent, new researchers, new infrastructure and business activity – in other words, in the entire ecosystem. Working on breakthroughs in research and innovation, on the development of new applications and markets, on the competences needed for this in, for example, the field of systems engineering and on the ethical, legal and social aspects of quantum technology [30].

In the ambition 'Collaboration for Excellence and Renewal' the focus is on collaboration. Given the developments in science and society, NWO is strongly committed to collaboration. NWO institutes fulfil a national role as centres of collaboration on strategically important topics. Collaboration between disciplines, between sectors and across the knowledge chain is an excellent way of contributing to surprising new insights. NWO is therefore devoting more attention to team science. NWO's contribution to the knowledge and innovation agenda of the top sectors and the promotion of public-public and public-private collaboration remains unchanged.

The last ambition 'Effective Use of Knowledge through Co-Design and Co-Creation' is an addition to the previous one. Next to scientific impact, research often has social impact and contributes to solving societal issues. NWO wants to promote knowledge sharing by working more closely with users. In doing so, it builds on the experience of various divisions of NWO. Public-private and public-public collaboration in research will remain possible in the coming strategy period.

10.4 European Union

In the whole world, funding for quantum technology development becomes available. Jesse Robbers: "In the Netherlands, money flows become available through the Growth Fund at the moment, but that also happens in Europe, in America, in Asia, in Oceania, and so on. Industry players are increasingly jumping on this technology; in the Netherlands, this is still somewhat limited, but it is happening nonetheless."

What is striking is that every country is investing in quantum development. The reasoning behind this is that they want to take advantage of other countries, especially countries that belong to another continent. Both Kees Eijkel and Dan Howell indicate that they would like to see the economic impact take place in Europe. Dan Howell: “I think it is important for Europe to take some kind of collective action to develop this technology.” Ingrid Romijn agrees to this, but “what we really miss here are the Cisco and Junipers of Europe. And there are hardly any, because all that industry is in America.”

The EU offers different types of funding, like grants, subsidies, financial instruments (loans, guarantees and equity), procurements (public contracts) and trust funds prizes [94]. Specially for the research in quantum development, the European Union launched in 2018 the EU 'Quantum Flagship' with the aim of turning weird physics into useful products. This initiative of the European Commissions contains a total of 1 billion euros of funding that is divided over 20 international consortia [95]. Quantum computers, quantum communications, quantum sensing and metrology, quantum simulations, and basic quantum research are all part of the quantum flagship. This long-term research and development programme aims to place Europe at the leading edge of the second quantum revolution. When scientists understood the rules of quantum mechanics and constructed devices that followed those rules, the first quantum revolution enabled breakthroughs such as the laser and transistor, the basic building block of computers. The second quantum revolution is when quantum mechanics is used to perform everything for you, such as transmitting information by entangling individual qubits. You are modifying quantum mechanics to achieve a goal, instead of having a device with interesting properties because of quantum mechanics [96].

With a budget of €1 billion from the EU, the Quantum Technologies Flagship is anticipated to support the work of quantum researchers over a ten-year period. The flagship, which was established in 2018, brings together academic institutions, business, and government funding to strengthen and grow European scientific leadership and expertise in quantum technology. Its mission is to support in the translation of European research into commercial solutions that fully use quantum’s disruptive potential [97]. Quantum computing, quantum simulation, quantum communication, and quantum metrology and sensing are among the four major application areas where it is funding work. It also finances research into the fundamental physics that underpins quantum technology, along with education and international collaboration in the field.

10.5 Industry

Industry is a very broad concept. In this thesis, industry refers to all companies that try to make a profit with their business or as it was said in the interviews: “Industry is the world of parties trying to make money with their technology.” In this part will be elaborated on the different type of companies involved in quantum development. This can be a private company, a corporate or a start-up. Each type of company has a different motive when it comes to quantum technologies, and they also play a different role in the development. Moreover, the companies can be active in different sectors, such as tech companies, financial companies, manufacturers, etc. Later in this section, a light will be shed on interesting sectors for the development of quantum technologies.

10.5.1 Corporates

Starting with the big companies, the corporates. Corporates have the knowledge, skills and resources to accelerate the process of growth and innovation. Moreover, they have access to a large international network. Corporates themselves have enough money to invest in a new technology. So, a corporate company is a very large, international enterprise with its own internal investment resources. But, as Kees Eijkel says: “The corporates may have internal investment resources, but they do not have customers yet.”

In the field of quantum, some of these companies have already started their own research into quantum technologies. Normally when the corporates start working on a new technology it becomes difficult for universities/research organizations to keep up. Corporates have the money and the people to really focus on a development and will take the lead in that development. Several interviewees stated, “Nobody can catch up with a corporate because they can be so focused. So once they start making the big money, well, you are screwed." Lawrence Gasman gives the following example of it: "There are quite a lot of large companies in this field already, including almost large and super large. I have no idea what IBM spends throughout the year, but tremendously large. But then you get a company like Cisco, which is more and more actively involved in quantum, but could never beat IBM."

The problem for companies investing in quantum development is that it is still unknown which technique will form the best quantum bits to make a quantum computer. This makes it difficult for a company to focus on a specific subject, and makes it very risky to invest in it. Companies like Google, IBM, Microsoft, and Intel are examples of companies that are already investing in the development of quantum. They each have their own teams of scientists working on the technology [98]. By comparison, Google and IBM use superconducting transmon quantum bits [99, 100], while Microsoft uses topological quantum bits [101]. Intel is using superconducting transmon quantum bits [102] as well as silicon spin quantum bits [103]. It is a risk for them to focus on a specific type of quantum bit, without knowing if it is the winning type. The reason they chose it anyway is because quantum computing has the potential to change the world. They see it as the Moonshot projects. They also run the risk of missing the boat if they do not start working on it now [104].

Other names of companies that appeared in the quantum field are: Fujitsu, Trumpf and Honeywell. These companies are working on building their own quantum computers. When we delve deeper into these companies, "it strikes us that the biggest players are largely American, that is the reality, especially in the quantum world," says Dan Howell. Ingrid Romijn also sees this: "Only in the Netherlands, and in Europe, it is unfortunately the case that there are no large(er) industrial parties."

In addition to the large tech companies, other types of companies are also getting involved in quantum. Of the corporates, only American companies such as J.P. Morgan and Merck are visible now. Lawrence Gasman talks about them: "J.P. Morgan, which is very actively exploring how quantum computing can help them, has put together a team. It is probably the first time J.P. Morgan has hired physicists in its 150 years of existence. It would not be something they would do, so they are not very involved in universities as far as I know, but they are looking for something different, they are just trying things out. It is very much a software and service kind of thing. On the materials side, the drug discovery side, I bet I know literally everybody is working on quantum. And also Merck, that is a huge drug company. So these are very small projects and universities are involved to some extent, but they are not trying to build companies around it, they are trying to build projects, so that is a little bit different."

Not all corporate companies try to develop quantum technologies on their own, some are working together with universities already. In Delft, QuTech has some very big industry partners that are driving some of the programmes. Microsoft and Intel are already a couple of years together with QuTech [33, 105]. Fujitsu is now one of the newer partners. In these collaborative projects, with Fujitsu, Microsoft and Intel, there is something in the company that the university does not have and will not get, but which is very useful for the development of research. Agreements have been made to make these collaborations a success. Kees Eijkel: "We do not get the exclusive rights to what we do, they give us money to do that research and only get those non-exclusive rights." Besides only doing the funding, the companies want to be more involved in the research: "They are already working with us, but want to put a few people here. They would then be fully integrated into our research programme, which is an even closer collaboration."

Next to the collaborations in Delft, there are more. Ingrid Romijn knows: "For example, Shell is collaborating with the University of Leiden for quantum simulations, because ultimately they want to develop certain materials faster."

In addition to the companies already involved, more companies would like to enter the quantum field, according to the interviews. They want to see companies that have the money to make investments and that have the courage to say 'we are looking fifteen years ahead, so this is what I am investing in'. As examples, they mention European companies such as Siemens, AMSL, Atos, Ericsson, and Nokia.

10.5.2 Large companies

Apart from the really big companies, the corporates, there are many more large companies. These large companies have the money, but lack the right knowledge and resources. Therefore, they are a great target group for universities to collaborate with. Some of those companies are already interested in quantum and have reached out for universities to collaborate on it, like KPN of ABN Amro in the Netherlands [106, 107]. From the US, for example, they are Cisco and Juniper, both telecommunications companies that have started selling network equipment. In the Netherlands, telecommunication companies are also interested in collaborating in the field of quantum technologies, but financial companies and consultancy firms are also beginning to show interest. Those companies are the frontrunners of their fields.

Most other companies are not doing anything with quantum. One reason is that it will be a long time before the first quantum computer is made and works, and it is not yet known which quantum bit it will use. That is why it is a risk to invest in it. Companies can do it because they have the people to work on it. But large companies have to find researchers from outside, which means you can keep the technology for yourself if it works. So you can not take full advantage of it, compared to competitors. Next to that, they do not have any knowledge about quantum, how it works, what can be done with it and how profit can be made out of it. Finding this out costs a lot of time and money, especially for someone without a background in physics, which is why many companies do not do this.

In the telecom industry, KPN was the first to show interest in the quantum field. KPN and QuTech have signed an agreement to collaborate on making quantum internet a reality. QuTech's research and development will be supported by KPN's infrastructure and locations [108]. Next to KPN, Jesse Robbers was in contact with another telecom party. “I talked to them about What do quantum networks mean for the telecom industry? What is going to happen there, what can you do with it, and how can you learn from it? Now they are also involved, working on a proof of concept for quantum key distribution technology.”

Although KPN was the first to get involved, not everything is going smooth there. Jesse Robbers explains: “As an example, within QuTech we had Victoria Lipinska for quite a long time. At one point she went to work for KPN as a quantum lead, as a quantum specialist. She was the only one within KPN who was involved with quantum. When Victoria went to another tech company, there was no successor. And that is a deathblow for a party like KPN, for an industrial party that had a direct link with QuTech, but also with other knowledge institutes, if that link disappears. It will take a lot of time to restart that relationship.”

Besides the telecommunications industry, the financial sector is also showing interest. ABN Amro is the frontrunner in the Netherlands in this field. Ingrid talked about the collaborative project they did with them: “We had a project together with ABN Amro, TNO space and QuTech on secure communication. For the development of Measurement-device independent (MDI) quantum key distribution (QKD) over free space connections. The latter was the technical part with TNO space, and ABN Amro was involved as a customer. So we made a financial transaction completely secure, and I think it ran for three weeks and really proved that it works. So ABN Amro's interest was really in the security of financial transactions and linking different banking structures.” In addition to working with ABN Amro, Ingrid has had discussions with ING and the Dutch bank to establish a partnership with them, but so far without success.

Another unexpected party starting to work in the field of quantum are the consulting firms. Capgemini is setting itself up as the frontrunner in this field [109], but it is not the only one to see potential in quantum technologies. They notice that something is going on, but they are not yet fully engaged, although they are certainly interested. That also indicates that a lot of attention is being paid to technology, or focused on it.

Jesse Robbers has another example of a company that was not expected that soon to appear in the quantum field: “Jesse: I think a good example is Bosch, Bosch is a kind of family business. It does not just look at the short term to make profit, but has a very clear strategy on how they want to proceed in the coming years. So they have also positioned people with a scientific background or the ability to make the bridge to science, who participate in major European developments around quantum, for example, and who are not judged on that." On their website, Bosch Global describes the choice of quantum as follows: "A century has passed since Einstein's era, and yet we're still blown away by the effects of quantum physics — and the practical applications of quantum technology are bound to be even more astonishing" [110].

10.5.3 Start-ups & Spin-offs

Compared to large companies, start-ups have no internal investment money at all. Moreover, almost all of them have roots in universities. What they have in common, however, is that they do not yet have any customers either. Furthermore, the start-ups differ from the large companies in the sense that they are not trying to build a complete quantum computer, but rather making components for quantum computers, cryptography, building test beds for quantum networks, etc. Those start-ups and spin-offs focus on a very specific quantum technology. These companies have no money of their own, but are funded by investors who believe in a specific technology. They also take the risk of not developing the 'winning' quantum bit. But with all these small companies, all focusing on a different technology, it is to be expected that one of them will succeed. Each start-up has its own specific focus, which also differs in the type of quantum bits they use. The ultimate quantum bit has not yet been found, so they all try to develop different ones, hoping that they have chosen the best one to eventually make a quantum computer.

Spin-offs arising from research institutions are new innovative companies directly resulting from scientific research. The innovative character can be in various aspects: a new technology, a new material, a new application or perhaps a combination of several. In quantum development, a spin-off can, for example, provides tools for quantum research to research groups at universities and companies. In this way, they can accelerate the research into quantum technology for various applications.

If a research group or a university has to develop all their high-tech hardware and software (which also has to communicate well with each other) themselves, it takes them years to have a system that is good enough for research into quantum technology and the development of a quantum computer. These spin-offs usually have experience in making a certain device, which saves time and therefore money for research groups. So they actually provide the tools with which scientists can conduct research into quantum technology [111].

If a start-up achieves good results, they become interesting to large companies that want to invest in quantum and include a start-up in their own company. Dan Howell pointed out the first time this happened in the Netherlands: "Qu&Co was the Amsterdam-based quantum software company. They were their own thing, and now they are part of Pascal. And so I do not know if that is good or bad."

10.5.4 SMEs

Besides corporates and start-ups, there are many more companies. Small and medium-sized enterprises (SMEs) are companies with no more than 250 employees and a turnover of up to 50 million euros, according to the definition of the European Commission [112]. These companies do not have the money to invest themselves in quantum or has external investors. The large companies do have the money to invest, but most of these companies are not at all involved with quantum at the moment. Mainly because they do not know what is possible with quantum and how they can benefit from it.

Although small and medium-sized enterprises (SMEs) are not closely involved in the development of quantum technology itself, they are nevertheless an indispensable link in the supply chain for quantum computing. They provide the 'enabling', the making of the wiring, the making of control boxes or parts of the chip. Lawrence Gasman describes them as: "The substantial companies, they are mainly public companies that do cryogenics, or control mechanisms or do even the chips."An example of such a company discussed in several interviews is BlueFors. They specialize in cryogen-free dilution refrigerator measuring devices for the quantum computing and information industries [113]. They do not really have a partnership with the universities, but more like a supplier partnership. It is a partner on whom the universities have a certain dependence, but who does not do his research within the university.

10.6 Sectors

Since the quantum computer is far from being finished and is not yet working, it is difficult to predict all the applications that can be implemented and that will be developed. Although much is still unknown, it is already possible to think of some applications that will become possible with a quantum computer. All the different sectors that are likely to be affected by quantum technologies are discussed in the interviews. An overview of these results is described below and made visible in Figure 10.1. What emerged is that there are three main directions in quantum development, namely quantum computing, quantum networks and quantum sensing. Each direction has a number of specific sectors that it will affect. The technology that will most influence the sector will be specified in the following paragraphs.

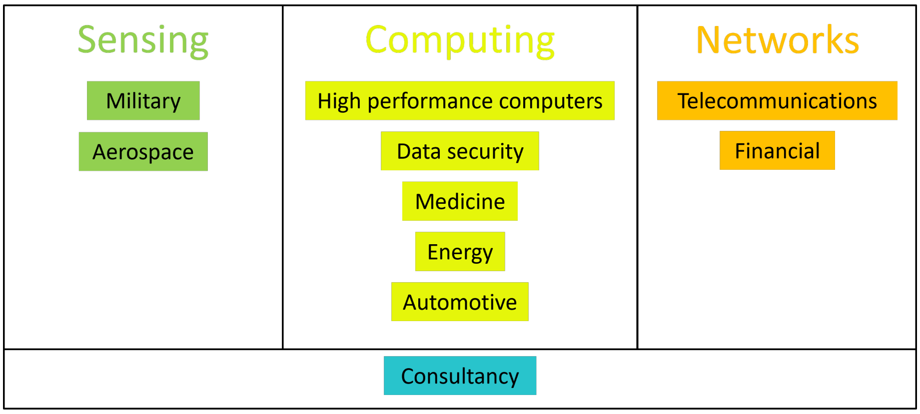


Figure 10.1: ***Sectors potentially affected by quantum technologies.*** *Based on the quantum technology that will affect the sector, the sectors can be divided into three groups: Sensing, Computing and Networks.*

High-performance computers

When it comes to quantum computers, companies that always work with very large computing powers, with high-performance computers, or with cloud computers, will have to work with them. They all have to deal with problems that can not be easily solved with regular or even supercomputers. The promise of the quantum computers is that it has the potential to solve certain problems much faster than 'ordinary' computers ever can. Quantum computers use the fundamental laws of quantum mechanics to do their calculations. This means that the qubits can be both 0 and 1 at the same time, which increases the computing capacity enormously. Companies that already rely on powerful computers will therefore benefit from the quantum computer once it is available for commercial use.

Telecommunications

The sector required for the development of quantum networks is the telecommunications industry. In the telecommunications industry, technological developments are always very fast. An important implication of quantum technology will be the usage of cryptography. With a quantum computer, current cryptography methods, based on multiplying large prime numbers, can be broken. This has major implications for all applications of secure communication (such as the Internet), end-to-end encryption (such as e-mail), storing data or passwords [114]. The first technological application of quantum networks under development is Quantum Key Distribution (QKD). It is a communication technology that uses quantum physics to create a cryptographic protocol for secure communication between two parties. It is expected that quantum computers will be able to decode encrypted messages that are currently believed to be highly secure. QKD creates a new encryption protocol that cannot be cracked by quantum computers. It is therefore important for the telecommunications industry to think about how they can secure their data and data flows as this new technology matures.

Data security

In addition to the telecommunications industry, all companies handling large amounts of data should rush to work with universities on secure data storage and new methods for communicating securely with sensitive data. The quantum computer will have a major impact on the current state of cybersecurity. They could be financial firms, healthcare organizations, governments, and so on. In the Netherlands, Jesse Robbers tells, a number of government agencies are sticking their necks out, Ministries of Defence, Security and Justice, Economic Affairs. And that the Ministry of Defence is very interested in quantum.

Recently the Dutch security service, AIVD, warned in the national newspaper for the quantum computer. The reason they did this, is that they see the progress that is made and the risks the new technique can have, namely cracking all current security measures. They warn for the moment the quantum computer can be used on larger scale outside the lab, it will just take time till there is enough calculation power to crack all encryption methods that are used nowadays [115].

Military

When it comes to quantum sensing, which involves complicated processes, you are automatically talking about military purposes, because sensors are very important there. Quantum sensors use ultra-cold atoms or photons that are precisely managed in certain 'quantum states' via superposition or entanglement. Quantum sensors can monitor minute variations in qualities like temperature, acceleration, gravity, and time by taking advantage of the fact that quantum states are extraordinarily sensitive to disturbances. Quantum sensing has the potential to change the way we measure and detect things. It not only allows for considerably more precise and sensitive measurements, but it also allows us to measure things we've never been able to measure before [116]. According to Lawrence Gasman, the military will belong to the group of the first actual users of quantum.

Quantum enhanced Global Positioning System (GPS) is an application that would very much like to be realised. The advantage of this application is a more accurate positioning, less vulnerability to hacking, indoor use, no dependence on satellites and no sensitivity to electromagnetic pulse attacks. The latter is critical, for example, in the event of a nuclear attack, when GPS systems are likely to fail [114]. This will affect all companies whose product or service is built on GPS, as well as governments and the military.

Aerospace

As well as the military, the aerospace industry can benefit a lot from the new quantum sensors. In aeroplanes there are many sensors installed. Sensors are used by aircraft not just as part of their navigation system, but also to monitor internal conditions and measure fluids such as fuel. Lawrence Gasman tells: “Aerospace is highly involved in quantum. Large companies, like Airbus and Boeing in particular, are very active in R&D in that field. They are an exception to the rule. Usually, end users get everything from another company, who are deeper into it. Aerospace is a little bit different. The big companies do much of the primary R&D themselves.” This makes companies in the aerospace sector attractive to work with.

Financial

Like the telecommunications sector, the financial sector will be affected by the advent of quantum networks and quantum key distribution technologies. Therefore, universities are already warning the financial world of what is to come and trying to convince them to cooperate, make scalable prototypes and think about the impact quantum will have on their business. In the US, several large financial companies are already working on quantum. In the Netherlands, ABN Amro is the frontrunner in this field.

Medicine

One sector that will benefit greatly from the emergence of quantum computers with high computing power is the pharmaceutical industry. The pharmaceutical industry revolves around the development of molecular formulations that become drugs to treat or cure diseases. R&D is so important to them that they spend a lot of money on it. The potential of quantum computers to mimic larger, more complicated molecules could revolutionize drug development. Using the quantum computer and quantum algorithms, new drugs can be created.

Energy

The development of new advanced chemicals and materials is critical not only in the pharmaceutical industry, but also in the energy industry. This includes anything from a better understanding of hydrocarbon characteristics to chemicals used in the production, transportation, and processing of oil and gas. Solving these difficulties necessitates high-precision simulations of molecules and reaction processes, which would otherwise take years to investigate experimentally. So quantum computing is also becoming very important in the energy sector.

Automotive

Lawrence Gasman explains that quantum is being worked on in the automotive industry. “Ford has something going on, VW had a project to use quantum computers for traffic management. And the reason they are interested is that with driverless cars, you have to make sure they do not collide with each other. So you need very sophisticated systems, and you need real time, very accurate data. Also, they all hope that in the future, it will be possible to get full automation in their factories.”

Consultancy

Consultancy is another type of sector that will be affected by developments in quantum technologies. Most likely, consulting companies will not be directly affected by these new technologies. But there will be a demand for companies that can help the industry understand, develop, add and integrate these new quantum technologies into their businesses. Consulting firms that cater to technical clients in the sectors described above must therefore prepare for this transition to quantum. They should prepare themselves with quantum knowledge and developments at universities, so that they can best help their clients in the transition to the use of quantum technologies.

Capgemini has been accelerating the quantum readiness of its clients through consulting, strategic, engineering and algorithmic development solutions, leveraging its Applied Innovation Exchange network and its engineering teams, as well as ecosystem alliance partners and network of peers [109].

10.7 Conclusion

In this chapter an overview of the stakeholders involved in the collaboration between universities and industry, as well as the sectors they expect to be involved in first, has been presented. Figure 10.2 provides an overview of all stakeholders and their relationships. Subsequently, the government gives money to the universities and the NWO. The NWO provides financial aid to the best scientific talent and research proposals from universities and industry. In addition to national funding, the EU has the Quantum Technology Flagship programme, from which it funds partnerships/consortia for the development of quantum technologies. Universities and industry are part of these collaborations/consortia that receive the funding.

Industry is the collective name for all companies that try to make a profit with their business. Five groups of companies are distinguished: the corporates, the large companies, the SMEs, the spin-offs and the start-ups. The corporates are very large, international companies with their own internal investment resources, knowledge, and skills. Large companies have the money, but lack the right knowledge and resources. SMEs lack both money, knowledge and skills. Spin-offs and start-ups are very similar, except that spin-offs originate from university research (or other research institutes) and start-ups do not. They both are depended on external investment money to grow their (still small) business. When these start-ups become successful in what they do, corporates might be interested in acquiring them to incorporate them into their own businesses.

If we look at the field of all stakeholders, it can be seen that the universities already have a partnership with the spin-offs. The spin-off works on something that was first developed within the universities, and tries to help the university further with their products. So close collaboration between these parties has already been established.

The potential lies in the collaboration between universities and large companies. The companies do not have the knowledge and expertise about quantum technology, but they are less dependent on financial aids from outside the organization. In collaboration with universities, university researchers can fill this gap and develop new quantum technologies together.

The companies that are potential partners for universities come from different sectors. Based on the quantum technology that will affect the sector, the sectors can be divided into three groups. This division is shown in Figure 10.1.

Quantum sensors will most likely influence the military sector and aerospace sector. Sensors already play a major role in these fields, and quantum sensors can take this a step further. For quantum networks, telecommunications and the financial sector are the first areas of influence. The secure communication made possible by a quantum network is very relevant to them. With the advent of the quantum computer, multiple sectors can benefit. The quantum computer can complement the sector of powerful computers or make new things possible in the medicine sector, energy or automobile industries. The quantum computer's great advantage is its enormous computing power in a currently unimaginably short time. The ability to decipher current encryption codes also makes the data security sector interesting.

One area that is not affected by any specific technological development, but by the general rise of quantum, is the consulting sector. There will be a new market for them to start helping other companies with what is possible and what they need to do.

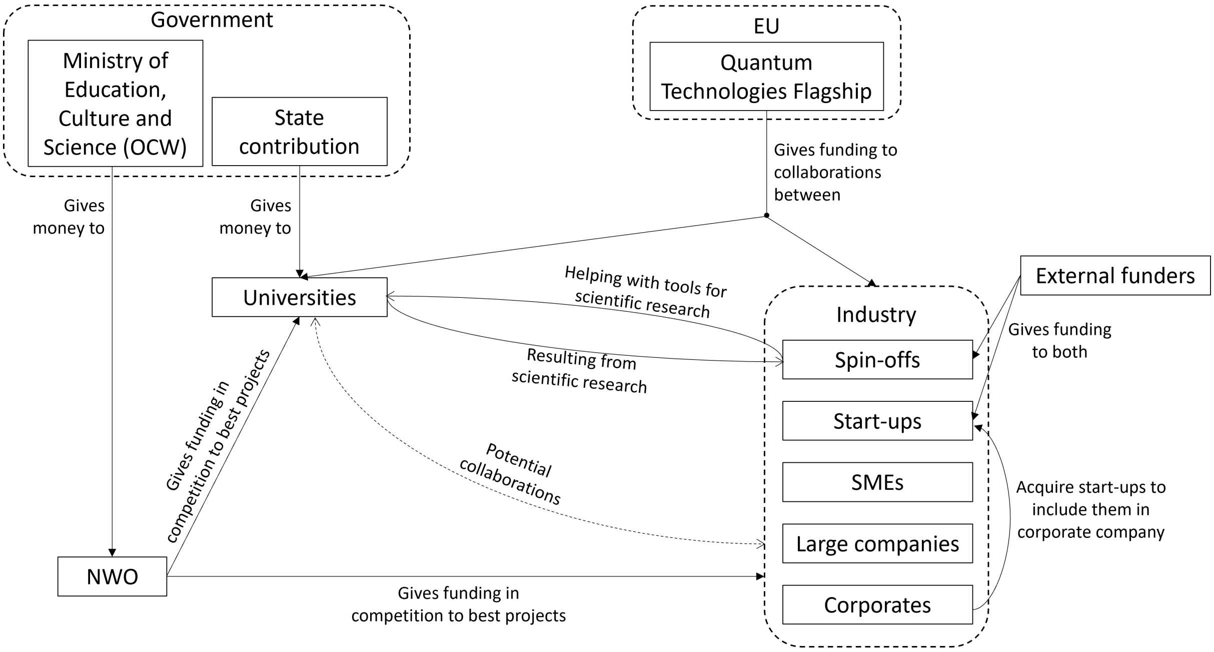


Figure 10.2: ***Stakeholder relations.*** *An overview of all stakeholders involved in University-Industry Collaborations, including specifications per stakeholder group. Also included are the relationships between the stakeholders and what these relationships entail.*

Chapter 11

Purpose

Collaborations between universities or collaborations between companies exist for a long time. Collaboration between universities and business has also existed for a long time, but in recent decades it has become increasingly common. That is because collaboration between universities and industry is becoming more widely recognized as a means of enhancing innovation through knowledge transfer [117]. Industry seeks for this collaboration to catch up with the rapid technological change, global competition and shorter product life cycles. They need to change their business plans and development strategies to survive. For universities, collaborating with industry gives them the opportunity to stay up front in their research fields. Universities have challenges with rising costs and problems with funding for their research, collaborating with industry gives them the money and confidence to produce new knowledge faster than those who do it all by themselves [118]. The increase in collaboration is not only initiated from the industry or university side, but universities are also under increasing public pressure to be perceived as engines of economic growth rather than as fulfilling the larger social mission (i.e., education and knowledge generation) that they have had in the past [117]. As a result of this pressure on both sides, there is a growing desire to establish university-industry collaborations aimed at improving institutional innovation and economic competitiveness through information exchange between academic and industrial fields [70].

Besides the motivation to collaborate based on pressure, there are more motivations for universities as well as industry to collaborate with each other. In literature, they state six critical conditions for interorganisational relationships [117, 119], which are: Necessity, Efficiency, Stability, Reciprocity, Legitimacy, and Asymmetry. These conditions can be seen as categories, containing the underlying the motivations for organizations to interact with one another. The motivations to collaborate differ for universities and industry, but all of those belong to one of the categories. When a motivation can belong to more than one category, it is assigned to the condition that is considered to be the most appropriate.

Each of the categories contains different motivations for collaboration. While searching for more articles with motivations for collaborations, not all stated motivations fitted nicely in the six categories. So to make the categories more suitable, they are grouped in the following categories: Economic, Human, Material/Knowledge, External factors, and Others. In Table 11.1 the 5 categories with the motivations in each category are shown. The motivations are split into those of universities and those of industry, since they differ per organizational form.

When reviewing the literature on motivations for collaborations, it turned out that in addition to organisational motivations, there were also several articles that referred to personal motivations for engaging in collaborations [77, 120]. These personal motivations focus on what drives individuals to engage in interpersonal collaboration, while organizational motivations are about what drives an organization to do so. For the purpose of finding the goal of collaboration between universities and industry in quantum technology, the focus will be on the organizational arguments. The personal motivations for wanting to establish a collaboration will be left out of consideration.

11.1 Universities

Economic

Collaboration with industry becomes part of the strategic policy of the universities [121]. This is partly due to the increase in grants from the government to promote university-industry collaborations [122]. Industry is also more interested in the research done at universities, in order to commercialise it for their own benefit. Therefore, they are funding more and more research projects. This makes the collaboration with industry more appealing to universities [123]. The shift to today's knowledge-based economy caused a change in university-industry collaborations. Besides only getting funding from industry, there are also business opportunities including exploitation of research capabilities and findings, as well as the use of intellectual property to obtain patents. Another option is in kind collaboration, but that belongs to the category Material and/or Knowledge.

Human

Although university students are trained on academic research, a lot of them will leave the university after graduation. In order to give their students a broad and realistic picture of their future job prospects, most universities collaborate with the business world to showcase their employment opportunities [124]. Besides, these university-industry collaborations give students, and the faculty, insights into the up-to-date application of the technologies, instructional case studies and practical problems through projects [117].

Material and/or Knowledge

Universities have a lot of academic knowledge in their fields of expertise, but sometimes lack to string with the current applications of that knowledge in practice. This is called the 'technology push', in which they strive to spark the market's interest in new items based on innovative solutions. On the other hand, industry partners can have the hands-on experience with the application, but lack the view on the current developments in the technology done by universities. This is called "market pull" in which products are provided the market demands [125]. As a result, universities may be encouraged to form partnerships with industry in order to benefit on these advantages for mutual benefit. This collaboration can both be based on knowledge sharing or use of equipment, or a combination of both. The speed in which new knowledge is developed increases, which puts a significant pressure on individual universities, forcing them to respond by collaborating with industry in order to stay on the cutting edge in all academic areas.

External factors

In the era of growing international competition and fast changing technology, governments are actively pushing university-industry collaborations as a way of enhancing innovation efficiency and, as a result, generating wealth creation [126]. The collaboration between universities and industry needs to be working properly to make sure the research is quickly transformed into technologies which can successfully contribute to the economy's growth and well-being. Universities are also under increasing societal (political and public) pressure to demonstrate greater entrepreneurship, social accountability, and overall economic importance [117].

Others

Research argues that publication in journals is an essential incentive for universities to collaborate with industry, as creating publicly accessible material would emphasize universities' fundamental role of spreading knowledge [122]. Another motivations for university scientists is to gain recognition from the industrial scientific community, which usually comes in the form of joint publications, presentations at important conferences, and research grants [127]. Furthermore, corporate funding assists faculty in performing research that leads to academic eminence.

11.2 Industry

Economic

There are several economical motivations for industry to create a collaboration with universities. Collaborations between universities and industry can boost R&D productivity, sales, and patenting activity [117]. Businesses also collaborate with universities because they can profit financially from innovative outputs, serendipitous research results, and cost savings, particularly in the areas of knowledge creation and exploitation. This can give the businesses a competitive advantage as well as improving their financial performances [128]. Another reason for industry to join a university-industry collaboration is to profit from the commercialization of university-based innovations. To be able to realize this commercialization, companies want exclusive rights to the technologies created by the universities. As a result, they are anxious about keeping control over university research along with proprietary control over technologies [129].

Human

Another reason for businesses to join university-industry collaborations is to obtain access to students for summer internships or job opportunities [130]. As a result of the engagement, most university-industry research programs aim to hire the brightest students. Faculty members or senior scientists do have time in which they are allowed to outside the university, in which they can be hired to consult in industry [121].

Material and/or Knowledge

A company can gain access to numerous of new competitive technologies through university-industry collaborations, reducing the distance between design and production. This would allow a company to quickly recover development costs for a specific product, as the agreements may include supply chain operations such as development and prototyping. Industry also have motivations for collaboration in the human capital development, such as proceeding professional education, state-of-the-art expertise/research facilities, and access to cutting-edge transdisciplinary technologies. They help mitigate the effect of today's shorter product life cycles (PLC) and thus improve competitive advantage [117]. The speed in which new knowledge is developed increases, is not only putting pressure on universities, but also on industry. Academic research has been found to improve companies' ability to solve specific challenging problems [131]. One of the bigger motivations to collaborate with universities, is industry's lack of in-house R&D. The collaboration is also valued by companies with their own R&D department because it reduces risks and makes better use of limited resources, such as personnel and capital [132]. When a company gets involved in a collaboration, where the university has more research networks at its disposal, it offers opportunities to be part of more complex collaborations. In these complex partnerships, more companies and universities can be involved to form a consortium. This is another motivation for the industry to enter into a collaboration with the university [133].

External factors

Governments have been forced to take measures to support research interactions between universities and industry as a result of global rapid changes in the competitive and technological environment, as governments believe that universities can help with economic revival if they publicize their knowledge and expertise through industry-affiliated collaborations [70]. As a result, governments have launched a number of regional and national research projects. Industry collaboration with universities is a must for most of these programs to be successful. Another motivation is the stimulation by the government of the growth of technology and research and development (R&D) through financial instruments like grants and tax credits, next to the creation of a legal environment encouraging R&D [126].

Others

Associating with a prestigious institution can also help a company's image and reputation. Relationships with well-known and respectable institutions, such as top research universities, can help a corporation gain credibility in the eyes of influential stakeholders [129].

Table 11.1: ***Purpose of university-industry collaborations.*** *All the purposes found in the literature are divided into five categories: Economic, Human, Material/Knowledge, External factors, and Others. The motivations have been split into those of universities and those of industry, as they differ by organisational form.*

	University	Industry
Economic	- Institutional strategic policy - Funding for research from industry, & including research assistance and lab equipment - Economic opportunities like use of research capabilities and results to obtain patents or use of intellectual property rights to obtain patents	- Strategic Institutional policy - Financial gain out of commercialization of university-based technologies - Cost savings (obtaining a licence to exploit foreign technology is simpler and cheaper) - Improving the technological capacity and economic competitiveness of companies - Reduction or sharing of risks - Maintain control over proprietary technology
Human	- University graduates gain more employment opportunities - Students and faculty are exposed to practical problems and applied technologies	- Students can be contracted for summer internship or jobs - Faculty members can be hired
Material/ Knowledge	- Get access to complementary expertise, cutting-edge equipment and facilities - Increased speed in knowledge creation and shift to knowledge based economy - Discover new application based on theory	- Development in human capital - Increased speed in knowledge creation and shift to knowledge based economy - Get access to complementary research expertise, cutting-edge equipment and facilities - Get contact to research networks or use them as a stepping stone to additional partnerships - Subcontract R & D (due to lack of in-house R & D) - Shortening product life cycle
External Factors	- React to changing governmental policies - Societal pressure - Help the industrial community/society	- React to changing governmental policies - Tax exemptions and subsidies are examples of national incentives for building such relationships - Contribution to regional or national economy
Others	- Paper publications - Encourage new ideas (through technology exchange) - Academics' thirst for eminence or recognition	- Leading-edge technologies have a multidisciplinary character - Enhancement of corporate image

11.3 Primary and secondary goals of collaboration

When looking more closely at the motives or goals that stakeholders pursue in order to achieve collaborations, one of the theories that emerges is the Goals-Plans-Action (GPA) theory. Originally, the Goals, Plans, and Action theory was intended to describe how people use their control over others to achieve their goals. However, the core concepts of the theory can be applied to any form of communication activity [134].

The Goals, Plans, Action theory was first established by Dillard in 1990 [135] to try to describe: What do people want to achieve through interaction? The Goals, Plans, and Actions theory includes the following concepts: each person has a primary and secondary goal, and plans are both deliberate and achievable. The primary goals guide plans and, ultimately, action. These goals are classified as primary because they are at the beginning of the goal-setting process. In the Goals, Plans, Action model, secondary goals are derived from primary goals and directly apply to the actions of the individual. There are two types of plans: strategic and tactical. Strategic plans outline what needs to be accomplished. Tactical plans outline how this will be accomplished. Both verbal and non-verbal messages can be used to carry out the action.

By applying this theory to the purpose of the collaboration, the goals of the GPA theory becomes motivations. For example, the primary motivation is one that was implanted in our brain when we were infants. We have an innate desire to do something, but we can not explain why, since there is not one. The activity itself provides us with energy for no apparent purpose. And the secondary motivation is a type of motivation that is influenced by our education and society. The outcome, not the deed, is what makes us happy. We feel good when we accomplish something (and not while). We lose motivation as soon as we do not entirely attain our goals [120].

The plans and actions of the GPA model in university-industry collaborations can be seen as the type of collaboration that is established. Therefore, this chapter will focus on the primary and secondary motivations, which can be seen as the purpose of the collaboration, and the type of collaboration (presenting the plans and actions) in the next chapter.

The primary goals from the GPA theory are defined as follows: gain assistance, share activity, give advice, change orientation, obtain permission, change relationship, and enforce rights and obligations [134]. These are very personal or individual goals. However, when applied to the primary motivations that organizations may have, they are very similar. If we focus on the collaboration between universities and industry, the primary motivations for universities may be different from those for industrial partners.

For universities, the main motivation to seek collaboration with industry may be to gain assistance or to share activities. Universities have the task of conducting scientific research in which they want to take the lead and make new discoveries. In order to do this in the best possible way and make applications that can be used in practice, outside university laboratories, they seek collaborations with industrial partners. One of the main motivations for doing so is to get help from the industrial partners, as they have knowledge and skills, but also money, to make these new applications possible. Sharing activities can also be a primary motivation for collaboration, as one gets further together than alone. Having multiple visions of a research project promotes its progress.

On the industry side, the primary motive of gaining assistance may also apply to collaborations with universities. But the primary goal of changing orientation may also play a role. While the university reaches out to industry to make academic research more practical, industry reaches out to universities to get knowledge and assistance on the latest discovered technologies that can help improve their products and services and grow their business. A change in orientation can also be a primary motivation for collaboration. If a company feels it has reached the maximum potential of its products and services, it will look for new opportunities to continue to grow.

In the Goals, Plans, Action model there are five secondary goals: identity, personal resource, relational resource, conversation management, and affect management [134], though not every goal will be applicable in every circumstance. The identity goals focus on the ethical and moral standards of communication. The personal resource goals are motivated by the desire to maintain or improve one's well-being, temporal and financial resources, and material goods. The relational resources are focussing on relationship management. With the conversation management goals is meant that by playing by the rules of conversation, interactants create a mutual understanding of what is occurring. Conversation management goals imply that the interactants establish a mutual understanding of what is going on by following the rules of conversation. The model also implies that people try to establish or sustain preferred affective states with the affect management goals.

For university-business partnerships, the secondary motives are less clear than the primary ones. From the definitions of the five secondary motives, it becomes clear in the first place that the collaboration is entered into by both parties out of a personal motivation to benefit from it. A collaboration only comes about when it seems that both parties stand to gain, otherwise there is no reason to set up the collaboration.

Another secondary motivation that is important is relational resources, in order to achieve successful collaboration. The same applies to the conversation management goals, where mutual understanding is very important. This mutual understanding is necessary to deal with the different expectations of both parties and to reach agreements. More about this can be found in Section 13.2.

11.4 Interviews

In the interviews, it also becomes clear that the goal of collaboration can be different for universities and industry. Kees Eijkel gives the following example: “The mission of QuTech is to make scalable prototypes. My mission is to create collaborations and to see if anything comes out of it. The outcome is often the commercialization of academic research into a practical product”. So he looks for strategic collaborations with parties that help them develop faster. Industrial parties are a good candidate to work with, because they have already managed to get it to an industrial level and there is often a lot of engineering in it, which a university never even gets to.

Jesse Robbers has a more industrial background, but his view of the motivations for university-industry partnerships is very similar. He says: “My motivation has always been to make new technology applicable for industry. In other words, to take technology developed by an organization like a university and see if you can now use it commercially in application services.”

In the interview with Dan Howell, who is working on the quantum ecosystem in Delft, his motivation for setting up this ecosystem with both industrial and academic partners lies more in the growth that can be made together. According to the Quantum Delft website: “Quantum Delft is a unique ecosystem that has been decades in the making: a hotspot for excellent scientists, engineers and entrepreneurs who are rigorously leading the way in quantum technology” [136]. With the establishment of the community and all parties involved settling in the same city, “the relationship with the university has become better and that of course helps with collaboration”, says Dan Howell.

Noting that things are a little different in the US, Lawrence Gasman has a different take on why industry wants to start developing quantum technologies: “Companies in the US see that they can make money with it. With new technologies come new applications that allow them to make more money.” This statement is rather harsh, but there is a grain of truth in it. If a collaboration on a new technology does not bring any benefit, the secondary motivational goal of 'personal resource' is not met, and the collaboration is very unlikely to come to fruition.

11.5 Conclusion

By combining the purposes found in the literature with the primary and secondary motivations for collaboration and the interview findings, an answer can be formulated to the purpose of collaboration between industry and universities in quantum technology. What becomes clear is that the purpose for universities is different from the purpose for industry. The answer to this sub-question is therefore two-folded.

University

When looking at what should be one of the primary motivations of universities, is that they want to gain assistance in developing quantum technologies in order to apply them into practical applications. The secondary benefits that universities gain from collaboration with industry based on this primary motivation can be found in the categories of Economic and External Factors. Economically, collaborations are good for industry research funding and economic opportunities such as the use of research capabilities and results to obtain patents or the use of intellectual property rights to obtain patents. In the context of External Factors, societal pressures and the mission of universities to help the industrial community & society play a role. This is also mentioned in the interviews of Jesse Robbers, where he indicates that he wants to make new technologies applicable to industry. He does this by making technology developed by a university commercially applicable in application services.

Another reason why universities would like to collaborate with industry, is their aim to share activities in order to exchange knowledge with business, to come up with new ideas faster. For this, the secondary motivations can be found in the category Material/Knowledge, where the motivations are 'gaining access to additional expertise, advanced equipment and facilities' and 'more speed in knowledge creation and shift to knowledge economy'. In the interviews, Dan Howell uses the Quantum Delft community as an example for this, where the university and start-ups are located in the same building, such that equipment and knowledge can be shared, and university research knowledge can be made practical in the start-ups.

So the main purpose for university should be:

- Commercialize research ideas and test their potential in society;
- Create faster new knowledge and shift to a knowledge economy.

Industry

A primary motivation for businesses to seek collaborations with universities, is that they want to change their orientation. When a company feels that it has reached the maximum potential of its products and services, it has to look for new opportunities to continue to grow. This can also be seen with a secondary motivation in the Economy category: to improve the technological capacity and economic competitiveness of companies. This is also what is stated in the interviews by Jesse Robbers: “If you are not up-to-date with the technological developments that are happening in your supply environment or that are coming from science, the risk is that others will take over your market position, and you will be taken by surprise.”

This is also the case when looking at the other primary motivation for the industry, which is to get assistance. Industry should turn to universities to gain knowledge and assistance on the latest discovered technologies that can help improve their products and services and grow their business. In the Material/Knowledge category, this is reflected as secondary motivation, such as ’increased speed in knowledge creation and shift to a knowledge-based economy’. Ingrid Romijn endorses this in her interview: “There is interest from companies that see that it is something that can affect society, that will affect businesses, and that they should do something with it.” So they seek collaboration with universities to get that knowledge.

So the main purpose for industry should be:

- Economically capturing useful knowledge to gain a competitive advantage;
- Access leading-edge research knowledge and infrastructures to grow their business.

Chapter 12

Type of collaboration

After establishing who the stakeholders of the collaboration are and what the aim of the collaboration should be, it has to be decided how this collaboration will look like.

12.1 Literature findings

Many articles have been written about the way in which the collaboration takes place. Schartinger et al. [132] wrote in their article that the methods utilized to transfer information between universities and industry depend on knowledge characteristics such as codification and involvement in technological artefacts. The potential economic worth of knowledge has an impact on how knowledge is shared between stakeholders, necessitating knowledge exchanges that ensure secrecy, build trust between actors, and allow for (exclusive) knowledge appropriation. They group the types of interactions they found into four categories: joint research (which includes R&D projects and joint publishing), contract research (which includes consulting and industry funding for university research), mobility (including movements of staff between universities and industry, as well as collaborative student supervision) and training (both way education between industry members and university researchers). They say each interaction is a combination of formalization of interaction, transfer of tacit knowledge and personal contact, each having a different share depending on the interaction that take place. As examples of collaboration, they mention joint research programmes, the use of university facilities by companies, the mobility of researchers between universities and companies, and conferences or other events in which companies and universities participate.

In the article of Perkmann et al. [70] they define multiple ways of collaboration between universities and industry. The first one is that the partners may agree on a purely financial quid-pro-quo, such as academic researchers working for a fee, or non-financial incentives, for example for academic research projects to get access to resources or data. Secondly, the partners generally pursue goals that go beyond the narrow boundaries of conducting research with a view to academic publication, and attempt to generate some benefit for the industry. As an example, the academic researchers can offer their expertise to provide new insights on application-oriented challenges, recommend solutions and solve problems for the industry. Lastly, in the article they talk about commercialization, which is a firm has the purpose of commercially exploiting a patented invention or a set of non-patented expertise. This can also be done by the university licensing a patented invention against the contractual receipt of royalties. In both ways, commercialization means that an academic invention is commercialized with the aim of financial gain.

In another paper of Perkmann & Walsh [59], they came up with three types of links between university and business. These types were based on the degree of relational involvement. In the first type, the relational involvement is high, which leads them to conclude that these are real relationships. Examples of things that belong in this high type are research partnerships and research services. In the second type, the relational involvement is medium, which means that there is mobility. Here, one can think of academic entrepreneurship or staff transfers. In the last type, relational involvement is low, so that only transfer takes place, such as commercialization of IP (e.g., licensing).

Bekkers & Bodas Freitas [61] state in their paper that there are 23 different ways in which universities interact with industry. The disciplinary origins, the characteristics of the researchers involved in the development and use of this knowledge, the characteristics of the underlying knowledge and the environment in which knowledge is created and used, all contribute to explaining the diversity of the possible ways. They arrive at the same kind of ways described by Schartinger et al. [132].

Combinging the ways of interaction described by Bekkers & Bodas Freitas [61] and Schartinger et al. [132] and separating them into the three types defined by Perkmann & Walsh [59], creates an overview of possible ways for university-industry interactions. This overview can be seen in Table 12.1.

Table 12.1: ***Possible ways of interaction for university-industry collaborations.*** *Based on the degree of relational involvement, the possible ways of interaction are broken down. The higher the level of relational involvement, the more interaction there is between universities and industry [59, 61, 132].*

High relation involvement	**Medium relational involvement**	**Low relational involvement**
Joint R&D projects	Personal (informal) contacts via membership of professional or alumni organizations	Licences of university-held patents and 'know-how' licences by firms
Joint publications	Informal meetings, talks, communications	Reading of scientific publications in (refereed) journals or books and professional publications and reports
Contract research	Financing of Ph.D. projects	Patent texts, as found in the patent office or in patent databases
Sharing facilities (e.g. laboratories, equipment, housing)	Joint supervision of students (both Ph.D. and Master)	Purchase of prototypes, developed at universities
Consultancy by university staff members	Students working as trainees	
Specific knowledge transfer activities	University graduates as employee	
Conferences or other events with firm and university participation	Flow of university staff members to industry positions	
	Temporary staff exchange (e.g. staff mobility programmes)	
	Staff holding positions in both a university and a business	
	Lectures at universities, held by firm members	
	Contract-based in-business education and training delivered by universities	
	Training of firm members	
	University spin-offs (as a source of knowledge)	

Context of collaboration

Since there are many ways of interacting between universities and business, each of them can best be used in a different situation. Bekkers & Bodas Freitas [61] article already states that the way of interacting is influenced by the environment in which knowledge is created and used. This indicates that the environment of the collaboration influences its creation.

An example of this is given in the article by Veugelers & Cassiman [137]. They argue that government can encourage collaboration through policy instruments such as cost-sharing and government R&D grants, which are monetary incentives to collaborate. This government incentive to collaborate usually leads to a high relational commitment between universities and industry. With government financial incentives, joint R&D projects can be set up or facilities can be shared between both collaboration partners.

Another example is that the region where stakeholders are located can also be important. The higher the R&D intensity of a region, the better universities perform in collaborations, according to Siegel et al. [65]. This can lead to both high relationship involvement and medium relationship involvement interactions. When the stakeholders are closer, it becomes easier to work together on a joint project or share facilities, as well as to exchange staff members, have university students do internships at the companies or give lectures and presentations for the other party. The overall industrial mix of the region is also important, as high-tech intensity seems to be related to collaboration and the creation of spin-offs [138].

12.2 Interview results

In the interviews, several of these ways of interaction are named with an example of what is happening now or as they think the collaborations should look like for the development of quantum technologies.

Collaborative research

Let's start simple. In the words of Kees Eijkel: "If the research is very practical, building a prototype and so on, then it is not so complicated." The goal of the project is then clear, and both parties have the same expectations of the result. It becomes more difficult if the collaborative research involves jointly investigating the opportunities for possible applications. This can be done in different ways, initiated by the universities, by an industrial partner who knows what he wants to do with the technology, or by an industrial partner who just comes to take a look because he realizes that it is important to do something with the technology in the future.

An example of university-initiated collaborative research comes from another field. Kees Eijkel: "At a certain point, the university did IT research for security, and they started working together with a few companies, because they wanted to get those IT solutions, for more secure internet, into the companies as soon as possible. And you can never do that as a university, you can not decide, but you can stick your neck out to make sure it happens." In this kind of collaboration, the university sees opportunities for industry and tries to involve companies in the research to work together and make the most useful applications of the technology.

There are some frontrunner companies in the field of quantum development that are working actively on quantum technologies together with universities. At QuTech, some research groups are working together with Intel. According to Ingrid Romijn: "Intel just knows, we have these chips, and at some point they are going to form this quantum processor. They really know where they want to go, and that is the hardware of the system. For those industrial parties, it is already very clear where they want to go and how that collaboration complements each other and what the roadmap is. We have a similar collaboration with Fujitsu, for example. They also already have a very clear idea that in five years' time we simply want a design of the future quantum computer." These collaborations happen mostly by big industry partners, that can afford to invest time and money in research.

The third category is made up of the companies that have just realised that they need to do something with quantum, but have no idea how yet. Jesse Robbers illustrates how this works in the area of quantum networks, where quantum key distribution technology is becoming feasible as an application for companies. “Quantum networks are starting to become so prototyped, commercialized, especially when it comes to quantum key distribution technology, that you, as a company, have to be very close to the ball now. That you have to do experiments on proof of concepts to learn: What does this mean for me? What can I do with it? How can I offer this in my products and services that I already offer, or should I do something else with it? Or should I text the practitioners who are now making the technology mature to say, hey, it is great that you are making this product, but if you colour it green it will not work in the existing infrastructure that we would like to have.” Companies urgently need to start cooperating with universities to remain innovative and maintain their current market position.

Sharing facilities

Another type of interaction is sharing of facilities. An example of this is given by Dan Howell: “Four of the five start-ups in the Quantum Delft ecosystem have currently been in a building of Delft University of Technology. So there has been a kind of relationship with the university to be in the university and that of course helps with the collaboration with a QuTech, researchers and things like that.” And where the university offers space for the start-ups to work, TNO offers them a rentable fridge. Many of the start-ups in the Delft ecosystem have rented time on this fridge to test their products, which has helped their company and their products grow. Sharing facilities between the partners in the Quantum Delft ecosystem thus helps quantum technology to develop faster.

Knowledge transfer activities

A way of interaction that has a high relation involvement are the knowledge transfer activities. This can be academic researchers giving talks about the use of quantum technologies in industry on conferences with both firm and university participation. But there are also other ways. Jesse Robbers has experience with these knowledge transfer activities between universities and industry and gives an example: “KPN was involved in the initial phase, the other telecom party was not. Two years ago, I entered into discussions with that telecom party at various levels about what quantum networks mean for the telecommunications industry. What is ultimately happening there, what can you do with it, and how can you learn from it? Because we started those discussions two years ago, as a result of the National Agenda, as a result of the developments that were taking place at QIA, that party is now fully on board, and we are now building proof of concepts with quantum key distribution technology in the Utrecht region.”

It is not self-evident that those companies are interested in quantum technologies. “They are open to new things and if you take them by the hand. If a few people within the organization at different levels say, yes, this is important to follow now and in the future, if we do things in time and have built up knowledge, we could start building commercial products and services. Then they are definitely open to it and ready for it.” Jesse Robbers gives another example: “If the pharmaceutical industry already has the prospect that they can do something with this in the future, and that this is also tangible, that it is actually a kind of promise, then the gap between technological development and applicability becomes smaller. And then you can start working with each other sooner.”

Training of firm members

Not all interactions between university and industry have to be collaborative research activities. Ingrid Romijn tells about a consultancy firm that is looking into quantum technologies: “Capgemini, for example, is very clearly jumping into this and is also building projects itself. So they have a team of people who are reading up and also talking to, for example, QuSoft, QuTech, to learn more about the technology. They do not build the technology themselves, but they are really on the application side.” Here, the collaboration lies in the training of the firm members, in order to teach them what quantum mechanics is and what its possibilities are in industry.

Flow of university graduates and staff members to industry positions

Next to get training for firm members, some companies decided to hire the people with quantum knowledge to form their own quantum team. Lawrence Gasman gives an example of this in the US: “There really is not a quantum computer made in financial services that can be used really effectively, yet. All the quantum team is trying to do is to determine how the quantum computer can be used.” This formation of own quantum teams and the lack of collaboration is only found in the conversation with Lawrence Gasman, and thus the development field in the US and not in Europe. Lawrence Gasman: “The end user groups who are just beginning to see what they can do with it are mostly doing that internally. With their own research teams. And they are also hiring good physicists and things. I do not think that any end users, I mean, there are a number of end users trying out different things, but they are not really building partnerships as far as I know.”

Investing

Investment can be seen as a way of interaction between industry and universities. Several ways of investing in quantum development emerged in the interviews. An illustration is given by Kees Eijkel: “I will give an example of an extreme in which we cooperate with KPN. They make fibres available, so actually money.” This is a business investment in university research. He also has a second example from the financial sector: “Most banks are willing to invest in the software piece, the application piece, but not in the underlying hardware solution.” This makes it difficult for a technology development like quantum mechanics, where first the hardware has to be finished before the software can be made applicable.

Lawrence Gasman has a different view on investment. He sees universities as the ones who can invest in start-up companies to accelerate the development of quantum technologies. “They can act as incubators for some of these companies, and the side effects of that are very important. It is hard to have non-profit incubators, so a university that focuses on the quantum information side is a great place to incubate small companies.” And while most people think of money when they think of investment, he thinks universities can offer more than that. “But it is not just money, it is mentoring and guidance. And by knowing so many people, they can push it in the direction that they are really becoming, like a huge mega mentor. And they also know in which direction to push things commercially.”

Thirdly, when companies get bigger, they no longer get money from universities to do research. The biggest companies, on the other hand, can give money to universities to do research. Lawrence Gasman says: “I mean, they are the ones with the money. If you give that to the universities, you know that will help. Projects get going.” More on funding for academic research comes later in this chapter.

Purchases

Besides funding university research, the bigger companies can also influence the quantum development in another way. There’s also the concept of acquisition and mergers, so bigger companies buying up smaller companies. Jesse Robbers gives an example: “When it happens that a large tech company gets its hands on a piece of knowledge, technology and develops it further or eventually buys a start-up and takes it over. Within three years, the startup’s management is fired, and the company is fully integrated into the tech company. The tech company is provided with several advantages as a result of this.” The scenario of startup companies that are purchased by the big ones is not one of the far future, but is already happening. Dan Howell expects that “we will probably see more of that as the startup companies grow and a successful bigger fish will look at them like, we can not do what they do, so let’s just acquire them.”.

Ecosystems

An outlier in the ways of interactions, is the creation of ecosystems of all involved parties. So not only universities, but also companies and governmental parties. In the US, Lawrence says: “Multiple firms are involved and even if you are talking about the big firms like IBM, that can do most of these things themselves, they still rely on the alliances with firms. Like in the case of IBM, Blueforce, which does their refrigeration basically.” And besides these industry alliances, there are other ecosystems around as well. “The other kind of partnerships that is around now, is industry partnerships that seek to promote quantum in general. So, we’ve got QEDC, in Europe you’ve got QuIC, now there is a German one as well.”

For the existing ecosystems in the Netherlands, such as Quantum Delta and Quantum Delft, much still needs to be done to support the companies. Dan Howell: “I think the biggest thing we can do to support the companies is help them develop the market, and that is not exactly easy. This technology is so new, its implications are still unknown. I see the whole kind of quantum field, especially what we do in quantum Delft, as if we are on the train, and we are literally laying the train track for the train. We do not know where it will go, as it will change, but you have to have that flexibility. But we are very much at the forefront of this new field.” The ecosystem should be barrier-free and can be seen as a pressure cooker for new quantum technologies. The more parties that join the ecosystem, the more new ideas can be conceived. But, says Dan Howell: “Keeping the ecosystem together gets harder the bigger you get. But having that campus, that infrastructure, that will also attract companies.”

12.3 Conclusion

In this chapter, the types of collaboration for university-industry collaborations in the field of quantum were discussed. The ways of interaction between universities and industry described in the literature are grouped in Table 12.1 according to the level of relational involvement. When comparing these ways with the ways mentioned in the interviews, it is striking that not all the ways of interaction from the literature are currently applicable to the development of quantum technologies.

Conducting joint R&D projects and collaborative research, sharing facilities or participating in knowledge transfer activities are often mentioned in the interviews. These forms of interaction have a high relational commitment. In the interviews with people in the field, these activities are seen as the most important. They think that only by really working together can industry be involved in the development of applicable quantum technologies, because industry cannot make it on its own. Sharing facilities is a start, with start-up companies in particular being able to benefit from the equipment that the university has, which is too expensive to buy themselves. Participation in knowledge transfer activities is a step that companies must take in order to become familiar with the possibilities of quantum technology. It is also the starting point for the business world to be able to determine how it will affect their products and services, and what actions they should take. According to the interviewees, collaborative research projects are the best way to involve industry and create applicable technologies for the field. By working together, the fundamental theories can be linked to make them practical.

Of the category requiring medium relational involvement, the training of members of the company and the flow of graduates and staff from universities into positions in industry are mentioned by the respondents. The training of the members of the company is mostly mentioned in the cases where partners from the industry are active in the consulting sector. These companies do not want to develop new quantum technologies themselves, but want to help other companies to get involved in the development. In order to do so, they need to know what is happening in the field and where the gaps are for other companies to start collaborating with the universities. On the other hand, the flow of university graduates and staff into positions in industry can be an incentive for a company to work on quantum technologies. If the company has someone with technological knowledge, this person can be the one to lead the collaboration with universities.

Investing and purchasing are other modes of interaction that emerged in the interviews, both of which fall into the category of low relational engagement. They were not so named in the literature, but in both cases there is no high interaction between industry and universities. Therefore, although these two forms of interaction play a role in the field of quantum technologies, they are less relevant for the development of a vision on collaboration.

To answer the question “which type of collaboration is most suitable for the development of quantum technology?”, conducting research in partnership with universities and industry is therefore the most suitable. Sharing facilities, participating in knowledge transfer activities and the transfer of university graduates and staff to positions in industry are applicable in the field of quantum development, but can be seen more as a basis. The real joint R&D projects have the promise of producing applicable technologies that can be used in industry, in the sectors that are first in line.

Chapter 13

Influence factors

In addition to the aspects of stakeholders, purpose and type of collaboration, there are some other aspects that are missing. Every collaboration has factors that have a positive influence, while other factors influence the collaboration negatively. Therefore, these factors are examined both in the literature and in the interviews.

13.1 Positive Influence Factors

13.1.1 Literature

The aspect of factors that have a positive influence on the creation or realization of collaboration comes in various forms. For example, in the study of Sjöö & Hellström [57] they identify key factors that enable business and universities to collaborate on innovation. While in the Fuentes & Dutrénit [62] study, they discuss the impact of driving forces on collaboration. Combining the information from these articles, and from Nielsen & Cappelen [68], provides insight into the possible drivers, benefits, and enablers for university-industry collaboration. Illustrations of this include trust, which is necessary for successful collaboration [68] and innovation capabilities and innovation strategy are important drivers for interaction [62].

Universities need funding to be able to carry out research. Conducting research is expensive, especially in the case of quantum technologies. For example, the research of Applied Physics into the link layer required a lot of expensive equipment. This included two quantum bits, both of which had to have a temperature of 5 Kelvin, multiple red and yellow (high-power) lasers at specific frequencies, arbitrary waveform generators, microcontroller units, optical lenses and mirrors and so on (see Figure 3.3). All in all, a lot of equipment is needed, and it costs a lot of money. And this is just for one setup. There are many more setups of research groups doing research on quantum technologies. Therefore, a lot of money is needed and that makes it a big influencing factor for entering into collaborations.

One of the driving forces behind university-industry collaborations may be the availability of non-governmental funding at the local level [57]. So the availability of public financing for R&D initiatives influences the level of collaboration [139]. When looking at the goals and types of collaboration, funding plays a role in both aspects. Thus, not only do government monetary incentives stimulate the establishment of collaboration, but funding from industry itself also creates an incentive for the university to collaborate with industry.

It is not only the funding of university research that is important; companies that invest heavily in R&D also play a greater role in collaboration. These companies have a greater absorptive capacity to learn from and work with universities [140]. Companies that invest in R&D have a more reciprocal background with universities, which makes the step to collaborate smaller. Often the companies that do invest in research also have a higher patent intensity and a higher patent value. As a result, they are also more inclined to collaborate with universities [141].

On the other hand, universities that encourage entrepreneurship are more involved in business than those that do not [142]. The organizational mentality of universities plays a major role in the distribution of money within the university. If the university values entrepreneurship, there will be more money available to approach the business community and work together on new technologies. If the university has a greater theoretical focus, there will be less incentive for the researcher to enter into these collaborations. So the focus of the university is important when creating partnerships with industry.

Another driver for collaboration is when somebody initiates projects and connecting them across the university-industry gap, as well as providing effective communication routes between businesses and relevant academic research outcomes. If this is missing, it is often seen as an obstacle to collaborate [57].

To be able to create a successful collaboration between universities and industry, high levels of trust and mutual interest are needed [68]. The lack of these, can be seen as negative influence factors and are discussed more in Section 13.2.

13.1.2 Interviews

Collaboration between universities and industry does not just happen. There have to be benefits and drivers for both sides for them to enter into a collaboration. In the interviews, several advantages of these collaborations are mentioned, some for universities, some for industry, but as Dan Howell said, “I think both sides can benefit in a way that is mutually beneficial.” In the coding, the elements benefit and motivation were treated separately, but during further analysis the quotes belonging to these elements turned out to be very coherent. Therefore, it was decided to combine all these quotes into a combined section, the positive influence factors. Some factors can be seen more as a driving force and others more as a benefit.

University perspective

From the university’s perspective, several advantages and drivers for collaboration with industry were mentioned in the interviews. The first driver of collaboration with parties from industry is that the technical level of industry is much higher. This level will never be reached within the universities because there is no need for it, but it is beneficial for academic research if it can make use of the technical products of industry to achieve better results. To make the most use of the technical level of industry, Kees Eijkel states: “As a university, we want to be surrounded by many companies that are relevant to the Netherlands and also relevant to our research. So a company that does something we cannot do and that we are really happy with when they are located nearby.”

The second advantage that emerged was that when large industrial partners are involved in research, they can bring in funding, expertise, equipment and whatnot. Funding is the most thought of advantage for involving industry in academic research, since getting funding for research is an ongoing struggle. An example of sharing equipment, is given by Dan Howell. He explains: “TNO basically has a rentable fridge. Many of the start-ups in the Delft ecosystem have rented time on this fridge, and it has really helped their business and their products grow. Because otherwise they would not have had access to a fridge, so they would not have been able to test their products.”

Not all companies are suitable for collaboration with universities, because it costs time, money, and energy. Therefore, from the universities’ perspective, the question is: what will the company bring to the university community? What will the company add? What is the outside benefit of working with the company? If a company really wants to invest in research, like funding a PhD, Masters, or something like that, to really get actively involved in the community, then there is ground for a collaboration. In that case, the university sees that this company is serious and that the company not just wanting to ’collaborate’ for their own short-term gain, but that they want to build a relationship. So with the right motivation from the company, the university can also benefit from the collaboration with industry.

Another motivation for involving industry in research is that it facilitates the transition from research in the laboratory to research outside the university as the technology develops. QuTech's mission, to create scalable prototypes, is based on the fact that they do not want to be just an academic undertaking, but want to create something that escapes the university and has a snowball effect, so to speak, in industry. That is why it is very important to build relationships with industrial partners. As an example, QuTech and Intel delivered the first industrially produced qubit [32]. That would have been a lot harder without the university-industry relationship. Howell: "If a university did not have such a strong relationship, it could be knocking at the door of a commercial facility for a long time and being ignored. And so I think these links, in very specific cases, really do lead to beneficial results." Apart from the difficulty without the relationship, some of this R&D can be done in a clean room at a university, as can the development. But the reality is that the reproducibility possible there is far from a commercial manufacturing facility.

At QuTech in Delft, hard work is being done on academic research into the construction of scalable prototypes of a quantum computer and an inherently secure quantum internet, based on the fundamental laws of quantum mechanics [31]. To make it useful to society, applications must also be made that can run on these quantum computers. This is not done at QuTech itself, so they need (industrial) partners to make these applications. A simple but impactful driver for collaboration.

Next to internal drivers, there are also external drivers for university. One of them comes from the government, as Kees Eijkel explains: "The government asks us: we would really like you to pay attention to what is the result of your research. You can do that very laid back, you can say we all have good people, so it will all work out. Or you can say, yes, but we are going the extra mile, and we are also trying to stick our necks out to speed up the process." Exactly this last point, is what universities should do, to attract industrial partners for the collaboration.

Industry perspective

On the business side, there are other advantages to working with academia. According to Jesse Robbers, the main reason for industry would be: "If they are involved in the research or the new technology at an early stage when it becomes applicable, it gives them a chance to learn from it. This means they can see what it could mean in their company or in their industry". They can draw conclusions from it, to determine how it can help them or what knowledge they still lack. The knowledge environment within the collaboration can be adapted accordingly. From a university perspective, it is very important to know what the demand is from industry. What is ultimately what they want the technology to do? When is it useful? If the potential applications that the company sees are different from what the university had thought, the scope of the research can be changed to allow the technology to evolve to be ready outside the lab. Also, when working together at an early stage and thinking about what can be applied from the technology that has been developed, proof of concepts can be built.

Not all academic research is interesting for industry, certain topics are more interesting than others because there are potential applications. To know which topics in the research are the most interesting, collaborations have to be made to get insight in all possibilities.

A big driver for industry to get involved in new technologies is their competitive position. According to Lawrence Gasman, an example of this can be found in the drug industry in the US. "Quantum seems to hold the possibility of a new direction for drug discovery that can solve problems that even a supercomputer cannot, because of the parallelism in a quantum processor. So, suppose they can do the calculations necessary to get them to a new drug, they become quite rich. So it is a motivation that drives every company." Therefore, it is also clear to him that companies do not have the option of not diving into quantum, because if competitors do it, you have to do it too. Jesse Robbers agrees with him: "If you are not aware in time of the technological developments that are in your supplier environment or that are coming from science, the risk is that others will take over your position, your proposition, your market approach and that you will be taken by surprise. Another risk is that if you are too slow to enter, that is, you have not been sufficiently involved, and that others will make off with your technology, and you will end up two-zero behind. That others will run off with your business proposition."

For Ingrid Romijn, the most important benefit for companies at the moment is the PR value. By showing that they are involved and investing, they show the world that they are a leader in their field, which has a high PR value.

Another incentive for companies to collaboration with universities is their interest in the academic talent and infrastructure facilities available at universities. Quantum mechanics is a physical theory that is quite complicated to understand and therefore even more difficult to make applicable to current business processes. To make it possible for companies to do something with quantum, they need the people, the academic talent. Dan Howell also explains: “When we are talking about quantum, clean rooms are the big deal. Obviously, some of the equipment in there is over a million euros apiece. This kind of technology is not something that a start-up or scale-up can easily afford to have on themselves. So, that kind of facility access is important.” If you look at the ecosystems that are emerging in the Netherlands, for example Quantum Delta NL and Quantum Delft, they are built from the ground up. To create a startup ecosystem, there are six pillars of success [143]. These pillars are: Human capital, Regulation, Markets, Infrastructure, Business networks and Capital. According to Dan Howell, the main requirement of companies is facilities and infrastructure. That is the biggest attraction after the academic talent.

Mutual perspective

In addition to the individual benefits to industry and universities of working together, there are also some overarching benefits. For example, if universities and industry start working together at an early stage and are the first to develop applications of quantum technology, the economic impact in Europe could be enormous. The importance of the location where the collaboration takes place will be discussed later in this chapter.

Jesse Robbers: “One of the expectations of the first generation of quantum network technologies is that they will help with data security. Since securing data is very crucial, and there are risks involved, in the government domain, the actual involvement of different parties in the exchange of data should start at a very early stage. Risks such as personal data security, state security or information intensity are present.” This means that there is a national interest in collaboration between industry, universities, and government to work on the development of quantum technologies.

According to Kees Eijkel, “I think the biggest drivers in the business are the fact that it is a fundamental and exciting new technological development that people expect a lot from. If you can do that for the first time, then new possibilities will arise. You can put the thunder on that. Only you do not know them yet.” If the universities work on quantum development and create useful proof of concepts, industry will join in later. “Any university that does something like this will attract the interest of industry because industry will also see the benefit of it. So I think the fact that both sides see the benefit speaks volumes about why it is important to both partners,” says Dan Howell.

Jesse Robbers does have a suggestion as to who should be the driving force in setting up these collaborations. It should be an enormous connector, with a large network in the industry, and nowadays also in science. Because in the quantum developments, connections are constantly being made between parties who have new ideas. If they are brought together, perhaps from a university or institute with something from industry, they can think about how it can be made applicable for yet another party. The driving forces to bring them together are people close to the scientific organization and who can really bridge the gap between what is happening in science, speak languages and bring added value to science itself on the one hand, and make connections with industry on the other. This should be an out-going person, who knows how to make links, who knows how to make the bridges between industry and university and who knows how to position himself in the strategic discussions.

13.1.3 Summary of positive influence factors

When comparing the positive influence factors from the literature with those from the interviews, the interviewees mentioned many more driving forces and advantages applicable to the field of quantum development than those found in the literature. This is positive, because it means that there are many ways in which the collaboration between industry and universities can be positively influenced.

One thing already found in the literature, and underlined by the interviews, is that funding plays an important role in collaboration. Whether it is government or industry funding, both are the driving force behind the creation of collaborative projects. Funding is the most frequently cited benefit for involving industry in academic research, as obtaining funding for research is an ongoing struggle.

Another point that emerges from the literature is that companies that already invest in R&D will play a greater role in collaborating with universities. This also emerged in interviews with companies that are already wondering what quantum technology can do for their business or industry. By doing R&D, new opportunities arise, and by doing R&D together with universities, more opportunities arise quickly.

Something that was mentioned a lot in the conversation with Jesse Robbers, and which also came up in the literature, is that having someone who initiates projects and connects them across the university-industry gap can be a great stimulus for partnerships. These business developers have insights into both worlds and can stimulate the creation of university-industry collaborations.

An argument that emerges only in the interviews, for example for universities, is the high technical level in industry that will never be reached in university laboratories. It is beneficial for academic research if it can make use of the technical products of industry to achieve better results. It is therefore an incentive for universities to seek collaboration with industry.

For the industry, a new argument is the benefit of the PR value for companies that start working on quantum. Since not so many companies dare to delve into quantum yet, those that do are the frontrunners and can use that for their PR value.

Another positive influence factor for businesses is to maintain their competitive position if they start working on quantum with universities. If they do not start working on quantum and competitors do, there is a risk of others taking over their market position. To remain competitive, therefore, it is necessary to collaborate on quantum technologies.

A mutual argument, which only comes up in the interviews, is the economic impact that these collaborations and new technologies can have in Europe. The potential of quantum technologies is expected to be great, so if those technologies can be developed in Europe, it will have a great positive economic impact.

Figure 13.1 gives an overview of all positive influencing factors for the partnerships for the development of quantum technologies. Again, these factors are divided into factors that exist from a university perspective, from an industry perspective and factors that apply to both.

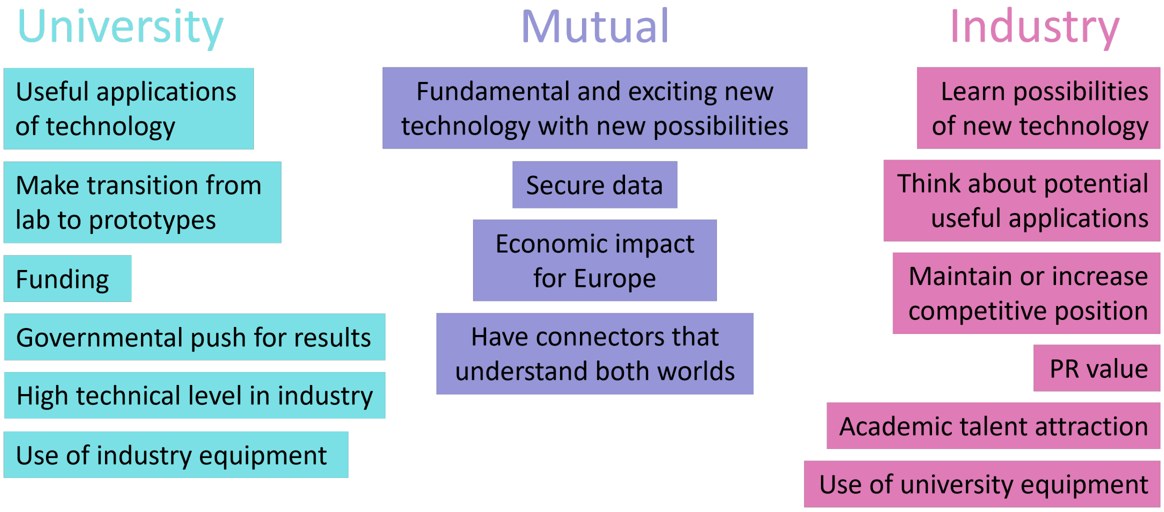


Figure 13.1: ***Positive influence factors overview.*** *All positive influence factors that exist for collaboration in the development of quantum technologies are divided into factors that exist from a university perspective, from an industry perspective, and factors that apply to both.*

13.2 Negative influence factors

13.2.1 Literature

Next to the positive side of collaboration with the drivers, benefits and enablers, there is also a negative side to it. These barriers are negatively influencing the creation or realization of collaboration. Again, in the article of Nielsen & Cappelen [68] they describe the barriers to knowledge transfer projects containing university-industry collaboration. One of the most interesting barriers they found is the resistance to participating in knowledge generating initiatives that do not yield a quick return on investment.

Just as funding is a positive influence factor for universities, money can be a negative factor for industry. As already explained in Section 13.1.1, doing research on quantum costs a lot of money. A company that wants to work with universities to develop new technologies must come up with large sums of money to make this research possible. And what is usually the case with research is that the outcome is insecure. For quantum, some applications have emerged from known theories, but have not yet been proven in practice at all. Investing in quantum for industry, therefore, comes with a risk. There is no guarantee that the applications that emerge from the collaborations will work in practice, and if they do, then usually not in the short term [30]. Investing in quantum therefore comes at a cost, with no guaranteed results. This has a negative impact on industry's willingness to collaborate with universities.

Another issue for universities is that companies sometimes struggle to envision what the result of a university–industry collaboration would look like [144]. Different expectations for the collaboration, hinders the effectiveness of the project. Companies that enter into a collaboration project with an open mind and curiosity are generally more satisfied with the result and the overall process than companies that started with clear expectations [68]. On the other side, business representatives complain that researchers' communication is ambiguous, resulting in a misunderstanding. In the study of Siegel et al. [65] the main barrier for university–industry technology transfer is the lack of understanding regarding the other party its norms. Also, the lack of knowledge and a mutually unfavourable perception of the other party are hampering the collaboration [57]. This means that expectations play an important role in collaborations, and if they are not discussed before the collaboration begins, this can cause a lot of hindrances.

Some other barrier for academic researchers to collaborate with industry is the fact that patents and industrial agreements have little or no impact on promotion and appointment decisions, which are based more on publications and federal research grants [65]. Moreover, collaborations have an impact on research productivity. Even when the collaborating academic researchers produce applied results, they do not immediately generate results for publishable articles. These publishable articles are still very important in the academic world. So although collaborations often produce new, academically significant insights and ideas, they are not as highly valued as publishable articles [70].

When it comes to university-industry relationships, issues of confidentiality and intellectual property rights come up a lot [68]. As already mentioned, a high level of trust and mutual interest is necessary for successful collaboration. So when there are problems with confidentiality or agreements on intellectual property rights, the level of trust will be very low. This will hinder university-industry collaboration.

Excessive bureaucracy is also an obstacle to effective technology transfer, according to both researchers and managers/entrepreneurs [57, 65].

Some critics worry that collaborating with industry may lead to a shift in researchers' priorities toward more applicable themes, at the expense of basic science's long-term advantages [145]. This is because academic researchers that work together with industry to commercialize their research, may keep their findings more secret than their open science colleagues [146].

There are also fears about the consequences that the development of quantum technologies will have. They can be compared to others that emerged in the past decades, like nanotechnology, genetic modification or synthetic biology. Those fears can cause research to be delayed or even halted. An example is the postponement due to public concern of the Stratospheric Particle Injection for Climate Engineering (SPICE) project, a geoengineering experiment [147]. Civil society organizations objected, claiming that a technical remedy would divert political and scientific attention away from greenhouse gas reduction. Another example: Public anxiety over genetically modified organisms (GMOs) and GM foods has hindered the commercialization of GM foods in Europe. These fears must be recognized and the mistakes of these earlier innovation programmes avoided, to prevent a deep-rooted "quantum phobia" from taking root [87].

13.2.2 Interviews

Although there are many drivers and advantages to collaborations between business and universities, there are also issues that stand in the way of this collaboration. These barriers to collaboration are also discussed in the interviews, and several obstacles are mentioned. A quote that stood out from the interviews about the barriers is: "The biggest challenge, I think, is finance, like the investment." Again, money is a big factor in collaborations. Besides the barriers that exist, there are also risks associated with the collaboration. These will also be discussed here.

University perspective

The biggest risk for universities in collaborating with companies is scientific integrity. When working with industry, the funding for the research usually comes from industry, and this creates a tension between independent academic research and industry wanting to influence the research. This influence usually comes from the desire to see results that are favourable to the company funding the research, so that they can show that they are the first and/or can make money from it. Dan Howell can confirm this: "From my personal experience outside quantum, it is always been that the companies are happy to support the research. But if something comes out of it that is detrimental to their business, then they want to be a bit more careful about that and have a bit of control." And even if the company does not directly influence the research, there can be a kind of reverse influence. Kees Eijkel explains: "Reverse influence is the concept that academics have become afraid to say things because they think that will make their money disappear."

Although there are many advantages to collaborate with industry, there are a number of things that hold universities back. One of the barriers is that, as a scientific community, you have to show that you are open to this kind of collaboration. “If you are not open to it, you risk missing opportunities to advance the technology in time or fail to involve the right industry players,” says Jesse Robbers.

Ingrid sees also a whole other risk: “One of the big risks for universities is expectation management, the hype. That because of all the positive stories and talk, companies think that the quantum computer can solve everything or that the quantum internet will be there tomorrow.” This quantum hype is something all interviewees recognize.

Industry perspective

Where universities must be open to collaboration with industry, companies must also be open to collaboration with academia. Especially when it comes to not just funding, but really working together on quantum development. This requires a specific ’boardroom mentality’, as Kees Eijkel calls it. That boardroom mentality means that the management of the company must be open to innovation with other parties. And this also means that companies look at it like, “can I make money with it in six months’ or a year’s time? If not, is it part of my core business? And if not, I will not do it.” they have the wrong mentality, according to Kees Eijkel.

An impediment for the industry to getting started with quantum is the fact that they have no (or insufficient) knowledge about quantum. This makes it difficult for them to see the potential applications of quantum technology in their company, which makes it hard to start investing in it. In fact, they do not have a good idea of what is possible. According to Ingrid Romijn, one solution to this problem is to have an internal advocate in the company. “That is someone who stands up and says: I’m going to pull this, this is so interesting here, we have to do something with it.” The advantage of having this person stand up and lead the way in a company is that the company has a direction on where to go with the technology and ideas on what it can do for their businesses. On the other hand, there is the risk that this person will leave and all the progress that is made will be gone, because no one else has invested enough in the technology within the company. If that happens, they can start all over again.

Jesse Robbers describes the main risk to the industry as follows: “The big risk is ultimately that you step into a technology that may ultimately have great promise, but that it does not come true. That you have made certain investments at the wrong time, often too early, and that you can therefore not make that investment come true.”

In the ecosystems being built in the Netherlands, there is another challenge. Dan Howell explains: “Namely, that at some point you start introducing competition. Like at the moment, all six of our companies, they do not compete with each other. They do different things, but there comes a point when you introduce a company into the community that is doing something that someone else is already doing.” This does not have to be a bad thing, since competition drives companies to a better result. But it is something to take into account as a challenge in this field.

Mutual perspective

The main mutual risks of collaborating with industry or universities, are the Intellectual Property (IP) rights. Multiple interviewees are focussing on this IP rights, and the importance of good regulations about it in university-industry collaborations. It is important to frame and regulate the boundaries between each other’s knowledge and rights in a very good way. That way it remains manageable, and no strange things can arise. “I think for any academic institution that is going to be developing these relationships, I think it’s really important that there is a strong legal agreement for both parties. So, they know how things will progress in any eventuality. So, if that some technology is developed, who does the IP belong to? And I think if you did not have that to start with, it could be quite rocky ground.”, Dan Howell. The intellectual property agreement should provide both parties with a level of protection and an understanding of the state of inventions and the commercialization of technology. It is important to have a balance of industry not suppressing research, even if it is not the outcome they want. A way must be found for both the company and the academic researcher to feel comfortable with the way things are done, which must be established in advance in order to establish a fruitful relationship.

Another barrier to be overcome before collaboration between industry and university begins is the expectation pattern. Industry and universities have different speeds in the way they work, different expectations of results and so on. This means that the expectations for a collaborative project must be stated and discussed before the project begins, so that everyone knows what is going to happen.

As already mentioned in the chapter on positive influence factors, it takes someone to build bridges between business and universities. Time and effort must be invested in making these partnerships possible, which also means that time and effort must be invested in finding the right people to build these bridges. The most obvious thing is that universities should do this, since they are working on the technology already. Jesse Robbers calls the people that should build the bridges, the business developers. "Universities have great difficulty or do not speak the language to take industrial parties by the hand and pull them at the right time. And because they do not speak the language, or because they do not have the people on board, the bridging function is not there. If you do not know how to make the bridge function and, you just need a certain type of people for that, then it will become very complicated. The tricky thing is, at the end of the day, if you have the wrong business developers on board, or business developers with the wrong mindset, they still can not bring what might be needed."

13.2.3 Summary of negative influence factors

The barriers and risks have a negative impact on collaborations for the development of quantum technologies. One of the first things found in the literature is resistance to participate in knowledge-generating initiatives because they do not provide a quick return on investment. This is also stated in the interviews. For example, several interviewees indicated that companies do not dare to invest in a technology of which it is not known whether it will ever work. So there is no willingness to invest in something uncertain, such as quantum technologies.

Another negative influence factor, found in both the literature and interviews, is that industry and universities have different expectations. Industry and universities have different speeds in the way they work, different expectations of results and so on, which will hamper collaboration when these are not discussed at the time of establishing the collaboration.

In addition to the expectations that need to be discussed, intellectual property rights and confidentiality are also two aspects that are seen as the main barriers to establish collaborations between universities and industry. It is important to demarcate and regulate the boundaries between each other's knowledge and rights in order to establish fruitful collaboration. Without strong agreement on these aspects, the collaboration is doomed to fail.

Enough has been written in the literature about the fear of new technologies, because they bring unknown and incomprehensible things with them. These fears can be a barrier to working with them, and therefore to collaboration between universities and industry. In the interviews, these fears were not really addressed, but the uncertainty about the realization of the quantum hype was mentioned more often. There are a lot of potential applications that should work on paper, but it is not certain whether it will be possible to make these applications work in practice. Uncertainties hinder collaboration in the development of quantum technologies.

In addition to the issues found in the literature, some other negative influencing factors were mentioned in the interviews. For example, scientific integrity is very important to universities, just as independent research can be. With industry funding, there is a risk that industry will want to influence the results of the research, which gets in the way of scientific standards.

Specifically for collaboration on quantum technologies, industry is hampered by its lack of quantum knowledge. When no one in the company has an idea of the potential of quantum technologies or what they can do for their business, it is a barrier to partnering with universities to work on them. So the industry needs to be educated about what quantum is and what it can offer.

Finally, as with the positive influence factors, if there is no one who can build a bridge between industry and universities, it becomes very difficult to set up a collaboration for the development of quantum technologies. A business developer is needed to connect both parties and get the collaboration going.

Figure 13.2 gives an overview of all negative influencing factors for the partnerships for the development of quantum technologies. Again, these factors are divided into factors that exist from a university perspective, from an industry perspective and factors that apply to both.

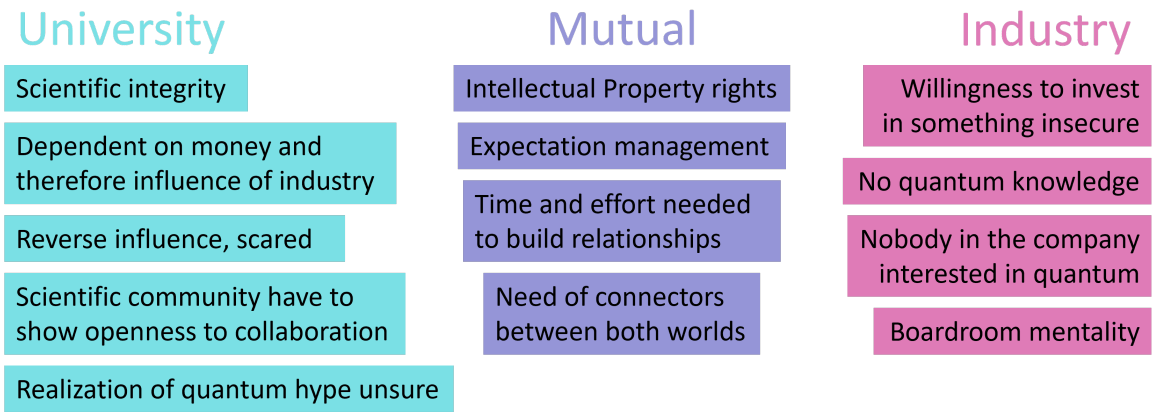


Figure 13.2: ***Negative influence factors overview.*** *All negative influence factors that exist for collaboration in the development of quantum technologies are divided into factors that exist from a university perspective, from an industry perspective, and factors that apply to both.*

Chapter 14

Next steps

In the previous chapters, answers are formulated for the first four sub-questions based on the literature findings and interview results. What became clear is that some things are mentioned in both, while others only appeared in one of them. By combining all these sub-question results and the vision of the interviewees on the future, the next steps on how universities and industry can collaborate can be formulated.

14.1 Vision on the future by the interviewees

The steps to be taken to establish collaborations between industry and universities in the development of quantum technologies is the result of the combination of the answers to the sub-questions. This reflects my interpretation of how collaborations should be established in the future, what the goal of the collaboration should be and what it should look like. In the interviews, the interviewees were asked how they see the future of quantum technologies, and this section contains the summary of their vision for the future.

14.1.1 Starting now

The commercialization of any technology area is always unique. In quantum, the fundamental breakthrough is the combination of quantum mechanics and its application through nanotechnology. This means that there is already a market for the technology, while the technology itself does not yet work.

There is a lot of talk about the quantum hype, and it is also a hot topic online. The risk of a quantum hype is that the technology can not meet the high expectations and that the bubble bursts. The hype stems from the fact that every new technology thinks it is different. Dan Howell: “But every technology goes through the same huge investment. Then it collapses, and then it finds some kind of equilibrium.” To keep the highs and lows from being so extreme, the Dutch approach is quite conservative, which helps to temper the hype around quantum. Dan Howell: “The investments in the Netherlands may be moderate compared to the US, I think the reality is that our companies are not over-hyping anything. They are not saying that we will have a quantum computer within a year and that we will change the world. They have clear roadmaps for the technology, for what they are going to deliver, and that will hopefully help to clarify the boom-and-bust cycle that the technology will go through.” Whatever the hype promises, it is unknown what quantum technologies will bring to our society as we know it today. Whether it is closer to hype or closer to pessimism, no one knows. But even if it changes only a small part of it, the implications are huge. Dan Howell: “This means it is important to be aware of quantum technology and embrace it if it suits your industry and if it is possible to embrace it and just see where it goes. Because if you do not, then once it becomes commonplace it may be too late. So it is a trade-off.”

Technological progress in the various fields of quantum development varies. Jesse Robbers: “I think that technological developments, when I look at quantum, are beginning to accelerate. It will take some time before there is a quantum computer, and the first is not expected to be available until 2030, with the form still unknown. For quantum networks, the first technological companies are now starting to get off the ground in order to create the first generation of quantum networks. For the quantum key distribution technology, the first commercial products and services are now available. Also in the Netherlands, but also elsewhere in European member states, start-ups are beginning to emerge in which quantum becomes applicable. In the field of quantum sensing, the first hardware is already available, but the application is not yet there."

He continues: "And that means that from the institutes, from science, from the knowledge institutes, but also as a company, you have to think very strategically about how do I proceed with this? How do I step in? How do I position myself? And how do I attract the right people to get into position?" Something that can help with these questions are proof of concepts built for potential applications of quantum technologies. They can act as a bridge between research and industry. Jesse Robbers commented on these proofs of concepts: "The only thing is that this is not going to produce anything for tomorrow or next year. It is only really going to deliver, of course, in the proof of concepts, but in the applicability in daily practice it is going to take a few years, and you have to dare to step over and invest in that."

Dan Howel sees opportunities in connecting quantum development with other technologies. "I think we can learn a lot from other fields and technologies and pick the best bits from all those other communities to see what works for us. And I think people within the quantum community are open to that. We are not proud; we do not have to reinvent the wheel. We can look at what is already there and use what works for us to our advantage."

14.1.2 Universities should take the lead

According to the interviewees, the party that have to take the lead in the process of setting up university-industry collaborations are the scientific organizations. Kees Eijkel: "I think universities should stick their necks out. The companies can not do that, they do not have the technology, they do not have the overview." Jesse Robbers adds to that: "You cannot approach all companies as a university. You have to look very strategically at which companies you are going to approach from a specific sector. Which companies can help us to eventually make products applicable in a preliminary phase? So you have to think very strategically, who am I going to invest time and energy in and which not."

Ingrid Romijn agrees that the universities should take the lead in the collaborations and also in the making of proof of concepts. "More results that show that it is really applicable and ready can get more companies involved in the development. What is very nice, of course, is the leading scientific results and Nature and Science papers, but what the industry is looking for are more the proofs of concepts. They show that something can also work outside the lab. So the moment you and a number of parties show that we have done this and that, and it makes the news, that attracts a lot of new parties."

Building on this, Dan Howell says: "Given that the government funding is now getting off the ground, there will certainly be a lot of growth on the academic side, guaranteed. Hopefully, that will also lead to growth on the industrial side, in terms of more start-ups. There is a lot of financial support provided to start-ups. And that in turn will lead to attracting more other companies to set up a European hub here in Delft."

All interviewees involved in quantum in the Netherlands agree that universities should start, but not much is said about how. Only Jesse Robbers elaborates: "I think it would be very good if you could attract people with a background in business and longer experience to such a university in a kind of business-development-strategy role and know how to make that bridge work." When these business developers are recruited, they need to decide which sectors to focus on. One suggestion given is that they should also play the game with industry associations or sectoral events that take place in certain environments. In the telecommunications industry, for example, there are many events, most of which are not focused on quantum but on a particular area of interest such as telecommunications infrastructure. It is precisely at these kinds of events that the business developers need to position themselves to connect with the companies. Another example, if you achieve a breakthrough with quantum key distribution, the business developers must also show up at those events, to position themselves there to tell the story.

At QuTech in Delft, they are working hard to create partnerships between university research and industry. Part of Ingrid Romijn's work belongs to this field, she says: "So looking for partners, organizing and creating partnerships with industry, or rather partnerships between the university, TNO and industrial parties." That there are people specifically hired for this purpose, is a big step forward, according to Jesse Robbers: "In Delft, a number of people at senior level are very clear that they have to involve people from the industry. These are people with different characters and a different background than is traditionally present in the Delft ecosystem. Without these people, they will not succeed in bridging the gap between universities and industry."

To help the business developers and universities, that not everything has to come from them, Quantum Delta is also setting up a project. This project is part of the overall programme in the Netherlands and will involve setting up field labs. These field labs are a kind of counter where companies can go with questions, and then there is a team of different universities and institutes that can help them. They can direct them to the partner that has the most knowledge in the area of the question. Ingrid Romijn: "At the moment there is quite a gap. On the one hand you can give a kind of very general story to companies: this is quantum technology, this is superposition and entanglement, this is the basis of quantum physics, this is how quantum computers and quantum internet work and this is what you can do with it in the future. Then there is nothing for a while, and then there is the research at QuTech to actually build it. And the piece in between is exactly what those field labs were set up for."

In addition to individual universities trying to establish partnerships with industrial parties, a broader approach is needed to involve an entire sector. Kees Eijkel explains: "We do not communicate with the entire field. It mainly takes place via links such as Quantum Delta, QIC, which is the quantum industry consortium of Europe, and also via things like conferences." Dan Howell adds: "I think the Quantum Delta initiative is great. I think it plays into the benefits. So basically, the Netherlands is a small country. It is easy, like this, that almost all quantum technology is covered somewhere in the Netherlands and having this national programme that gets the financial support of the government, but then also kind of coordinating that is really valuable."

14.1.3 Industry can not stay behind

It is not only the universities that must roll up their sleeves and try to establish partnerships with industry. Jesse Robbers: "You also have to be able to mobilize the companies to make people available, to free up time for this bridging function from the knowledge institutions." And the companies that want to bury their heads in the sand will be disappointed, because if a fraction of what is being hyped becomes reality, it will be significant. Dan Howell: "From a business perspective, it is important that we do not stand still. Otherwise, we are no longer the best, and we will be overtaken by everyone else. So we have to keep moving forward to stay ahead." The consensus is that the industry cannot wait for quantum to become a reality, but must start now. And fortunately, the first companies are starting to get involved. Ingrid Romijn: "The users, i.e., the banks, chemical companies, energy concerns, governments, etc., are now sticking their feet in the water a bit, and it will really depend on how fast the development of the hardware and the software goes, how actively they will get involved. That is very difficult to predict. If there are huge breakthroughs in the next three years, they will all be knocking on the door in three years' time. And if those breakthroughs do not happen, then they will pull out."

Jesse Robbers thinks further and believes that companies should do more: "I think it is also important to set a point on the horizon. Quantum computers and quantum internet are going in a certain direction, so be sure that it might be a bit further on the horizon than the point we are setting today, but that it will be somewhere close is in the line of expectation. So you have to anticipate that and be flexible."

In addition to the companies belonging to the sectors that are seen as potential end-users, consultancy firms are also starting to show an interest in quantum development. Ingrid Romijn: "Consultancies see that this is something that could affect society, that will have an impact on companies, the banking sector, governments, and so on. So an interface is needed to make the technology understandable and to make that link. And that is where these consultancies are kind of jumping in now."

14.1.4 The first companies start working on quantum

Companies are making a small start to delve into quantum and what it can do for them. Although there are some companies that really dive into it, most just come to look around. Kees Eijkel describes it as "Everyone is doing something. They take a course now and then, but real projects do not really get off the ground yet." Lawrence Gasman has a metaphorical description for it: "We are seeing more and more big companies sticking a toe in the quantum sea." Both agree that this is just the beginning of industry involvement in quantum technologies. And while large companies shout from the rooftops that they are leaders in their field, much of what they are doing is just a beginning. As an example, "If you look at IBM, IBM is arguably the biggest quantum company in terms of revenue, and people and everything else. But if you look at the income statement and IBM's profit and loss, you do not see much there about quantum. It is just minuscule. The same would be true for Google." And also, when he talks to them, Lawrence Gasman experiences their lack of knowledge on quantum. When he asks them to speak about quantum at a conference, he gets the following response: "I'm a bit scared about doing this, because we do not really know that much about quantum. We've only been doing this for a year, and yes we mess around, and we like to talk, but we are going to say we do not know anything." This uncertainty from even the big companies is holding them back, but could also be a motivation for other companies, he says. "I said nobody really knows. You guys use supercomputers, you do really useful things on your supercomputers. But I ask you to share: what is your experience so far with quantum?" The answer to this question can be very valuable for others to get them over the threshold and into quantum.

Ingrid Romijn also sees other things happening in the field: "What I see at the moment is that a lot of technology from universities is finding its way into small companies, start-ups, so there are a lot of spin-offs." On the companies participating in the development of quantum technology, she says the following: "So you have the hardware companies and the software companies, the suppliers. On the one hand, those are the ones who build it, and those are the startups and the larger companies like Intel and IBM. They just make the hardware and the software, and they are already stepping in. There are investments for that as well, so those startups are growing and the larger companies are also investing millions. So I expect that this will only increase and in the next ten years there will be mergers, companies falling over and new companies joining."

In addition to the companies resulting from university research, large companies are also setting up quantum subsidiaries in order to really reap the benefits of being a smaller company. One example is Google's parent company Alphabet, which spun off Sandbox, a computational quantum software startup. A second example is the merger of Honeywell Quantum Solutions and Cambridge Quantum Computing, an English software company, to create Quantinuum. Lawrence thinks the reasoning behind it is "to have all the advantages of small companies, but they do not really have to worry. Because if they spun off, that money comes with the deal."

Next to the spin-offs, start-ups and big companies, also SME's and large companies show interest in the quantum development. Ingrid Romijn: "What is also really changing is the interest from, for example, companies like Deloitte, the consultancy firms." Jesse adds to that: "What you see is that the choice for a company like KPN, from the parties in that industry, is to be very close to the technological developments that are taking place. And to think about what that means for your business formation, for your product or your service, that lives up to your mission." In order to help those telecommunication companies, he is very keen to see if other telecoms parties can be involved in the quantum key distribution developments that are taking place.

14.2 Vision of collaboration in quantum technologies

The answers to the first four sub-questions in combination with the vision of the future by the interviewees form the basis for the next steps within which collaborations for the development of quantum technologies can be established. All answers are combined with the current situation to provide a picture of what such collaborations should look like and how they can be set up.

From the types of collaboration and the negative influence factors, it has become clear that knowledge about quantum is necessary to start developing new technologies. Universities currently have the most knowledge about quantum, while industry lacks this knowledge. As already mentioned in Section 8.4 this imbalance creates a situation of technology-push. This was an undesirable situation, so industry had to be involved in the development of quantum technologies. However, before one has sufficient knowledge and is ready to enter into collaborations to work on quantum, two other steps must be taken. These steps are broadly outlined here; they will be explained in more detail in the following sections.

The first step in forming a collaboration on quantum technologies is for the industry party to become aware of the existence of quantum and what quantum may mean for the industry. If one is not aware of the existence of a technology, it becomes very difficult to get started with it. Becoming aware of quantum technologies is the first step to getting involved in quantum development.

The second step is to accept the advent of quantum technologies, although it is not certain in what time frame they become practically available. This can be done through knowledge transfer activities or the flow of university graduates and staff into positions in industry. However, as already mentioned in Section 12.3, this is the basis of collaboration in the field of quantum technologies. When the acceptance of quantum is there, the step can be taken to actually work on it and make it applicable.

The driving force behind taking the step from acceptance to working on it and forming partnerships are the positive influencing factors. Together with the intended goals of the collaboration, these positive factors are the drivers for taking the next step. The negative influencing factors are impediments to taking the next step. Figure 14.1 shows the steps to take.

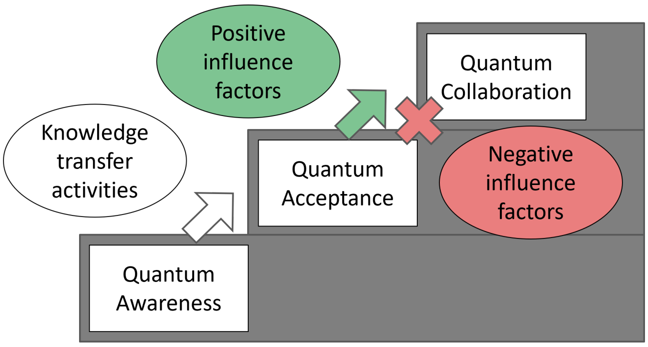


Figure 14.1: ***The steps to collaboration.*** *The first step to be taken is from awareness of the technology to acceptance, which can be stimulated by knowledge transfer activities. Once the quantum is accepted, the next step is to start implementing it by creating collaborations. The positive influencing factors are the driving forces and the negative influencing factors are the barriers.*

The idea of three steps to achieve collaboration is based on the hierarchy of effects. This model was developed by Lavidge & Steiner in 1961, and includes the six steps a customer goes through when purchasing a product [148]. The six steps in the hierarchy of effects are awareness, knowledge, liking, preference, conviction, and purchase. It is a step-by-step model, meaning that each step must be overcome before the next step can be taken. How each step is taken differs as the level of attitude towards the end goal changes. This principle of having steps to reach the end goal is also used in the next steps in the development of quantum technologies.

In the next steps for quantum, the number of steps is reduced from six to three. For creating partnerships, the step of knowledge is included in the step from awareness to acceptance. Having sufficient knowledge about quantum (not necessarily about collaborations) is necessary to take the step. The step of liking has been removed from the model, as it did not seem to fit the model. In technology collaborations, there are more technologies that can influence the business process of companies, but they will have a different effect and are therefore not comparable in this situation. The step of preference has changed into the step of acceptance. A company must prefer the technology, or accept it, to achieve this step. The step of conviction is included in making the step from acceptance to collaboration. The conviction must be based on comparing the positive points with the negative points. Whereby the positive points drive the conviction, while the negative points slow it down. The final step in the hierarchy of effects is purchase, in the case of quantum, thus collaboration. Buying quantum products or technologies might become possible for companies in the (distant) future, but first those technologies have to be developed and converted into practical applications.

The idea of three steps to achieve collaboration turns out to be not entirely new. In the article by Rutledge & Abell, they introduce the Awareness/Acceptance/Action Model (AAAM) [149]. In that article, they established the model for applying mindfulness ideas derived from Eastern philosophy to HIV/AIDS stigma. In a subsequent article, Abell & Rutledge apply this model to the development of mindful collaboration in HIV/AIDS research [150]. They believe that “the deep-seated obstacles encountered in collaboration can be usefully approached by examining the underlying assumptions, biases and expectations of the partners”. They seek to use the AAAM to understand the key components of functional collaboration.

They explain the AAAM model as follows: To avoid responding hastily, *awareness* begins with looking carefully and paying complete attention to the spectrum of one’s original experience. We try to see how our feelings, emotions, and associations affect how we react to a specific person or circumstance by observing them. The second element is attentive listening, which is paying undivided attention to a set of indications conveyed by another person. We try to decipher their needs and desires by observing both verbal and non-verbal cues. *Acceptance* entails fully understanding the genuine nature of our very own attitudes and preconceptions, including any inconsistencies between what we know cognitively and what we feel or act out in social situations. Acceptance in the context of collaboration entails avoiding ignorance of the mutual influence of discrepancies on partners’ ability to collaborate constructively. *Action* entails converting awareness and acceptance into thoughtful responses rather than rash reactions. In this case, intentionality implies attempting to eliminate misconceptions that obstruct knowledge and constructive interaction.

Their explanation is very personal, which means that it is aimed at an individual person who is trying to establish a collaboration with another person. In quantum technology, the collaborations are not necessarily between two individual persons with different backgrounds, but are more like two different organizations that have to work together. Therefore, in the field of the development of quantum technologies, the steps of awareness, acceptance and collaboration can be explained as in the following sections.

14.2.1 Quantum Awareness

It is becoming increasingly difficult not to have heard of quantum or quantum technologies, as there is enormous hype about the potential of quantum mechanics in new applications for the future. Just think of the quantum computer that can perform difficult calculations much faster than a normal computer ever could, or quantum communications that are so secure that no one can ever intercept them. Most people will have heard of it, but probably see it as science fiction or something they will never have to deal with. The fact that they know a little about quantum means that they are aware of the existence of the technology. That is the first step. The next step is to make them accept, from this small awareness, that the technology will affect their industry and therefore their business. This can be done through knowledge transfer activities.

14.2.2 Quantum Acceptance

The acceptance of the arrival of quantum technologies can be done in different ways, and each company has its own way. What they have in common is that to fully accept a technology, knowledge of it is required. This knowledge is usually provided by universities that conduct research on that subject. This is where the first forms of collaboration between universities and companies come about. This can happen in a passive way, such as companies reading articles about quantum in newspapers or reading scientific literature on quantum developments. It can also happen in a more active way, with both companies establishing contacts with universities and universities establishing contacts with industry. Examples are the knowledge transfer activities, such as lectures, presentations at conferences, or conducting conversations with a potential collaboration partner. These forms of collaboration are based on creating attention and understanding for what is happening in the field of quantum development. The actions to follow are the realization questions for all stakeholders, such as: “What does this technology entail? What is going to happen in the next few years? How can I learn from it? What can I do with it?”. This raises the awareness needed to accept a technology and makes you more willing to do something with it.

A recommendation that Lawrence Gasman makes about universities does reflect the feeling that universities need to have in order to be successful in collaborations in the field of quantum technologies: “Universities can invest in quantum technologies. Of course, they need to be serious about it. There is a university that sort of want to have a quantum programme, but they are not particularly willing to put any money into it. So, nothing’s really happening in this particular university. So, they need enthusiasm from the university, that is the way they could invest in it.” To be successful in partnerships, universities must really be willing to put in the time and effort. If they do not, it is unlikely to work.

In addition to the universities’ enthusiasm for the research, they can also take a step forward and show the industry their willingness for collaboration. One initiative to this end is a European platform, started from the Netherlands, called Quantum for Business. This is a ’platform for quantum technology that educates, connects and guides frontrunner companies that want to lead the quantum revolution’ [151]. Quantum for Business is a not-for-profit collaborative initiative that unlocks quantum knowledge, harnesses the potential of quantum and makes it available to businesses, promoting the adoption of quantum technology. The founders of this platform are TNO, QuTech and The Cronos Group. By not only focusing on the educational side, i.e., what is quantum, but also on the application side, i.e., what can you do with quantum in your sector, the platform offers a great starting point for companies that want to get involved and enter into collaborations with universities.

14.2.3 Quantum Collaboration

With the acceptance of the technology, collaboration to work on it and develop quantum technology is still a long way off. At this point, the positive influencing factors discussed in Section 13.1 are the driving force to move from acceptance of the technology to actually working on it. These positive influence factors for universities are already largely observed by them. QuTech, in particular, is seeking more collaboration with industry. The positive factors for industry, on the other hand, are less well known. These factors must therefore become part of the knowledge that industry must gather before it can move forward. This can be done passively, by listing the factors on a website. But it can also be done actively through presentations at conferences and lectures at companies by members of the university, just as was necessary to get them to accept the technology.

Besides the positive factors that encourage the establishment of collaboration, there are the negative influencing factors that act as barriers. To get to the point where collaboration becomes a possibility, these barriers must be overcome. As a metaphor for this situation, think of two people (university and industry) who want to come together, the positive factors drive the desire to come together. But, there is a wall between them that needs to be broken down, each brick represents a negative factor that acts as a barrier to be overcome. Only when all the barriers are down, a stable collaboration between universities and businesses can be made possible. To make the negative factors hindering the creation of collaboration more visible, a figure has been made. What is shown in Figure 14.2 is the brick wall, with the university on one side and industry on the other. Both want to come together (due to the positive influence factors acting as driving force), but there are barriers in the way. Only when all barriers have been removed the collaboration become possible. In Section 14.2.4 more details can be found on how those barriers can be removed.

The barriers are divided into three categories. The factors that have a negative influence on the university, the industry and factors that are mutually hindering. These factors can be distinguished by the colours they have been given. The blue factors belong to the university, the red to industry, and the purple to both. The factors are identified as barriers in both the interviews as in the literature. In Table 14.1 those factors are also shown.

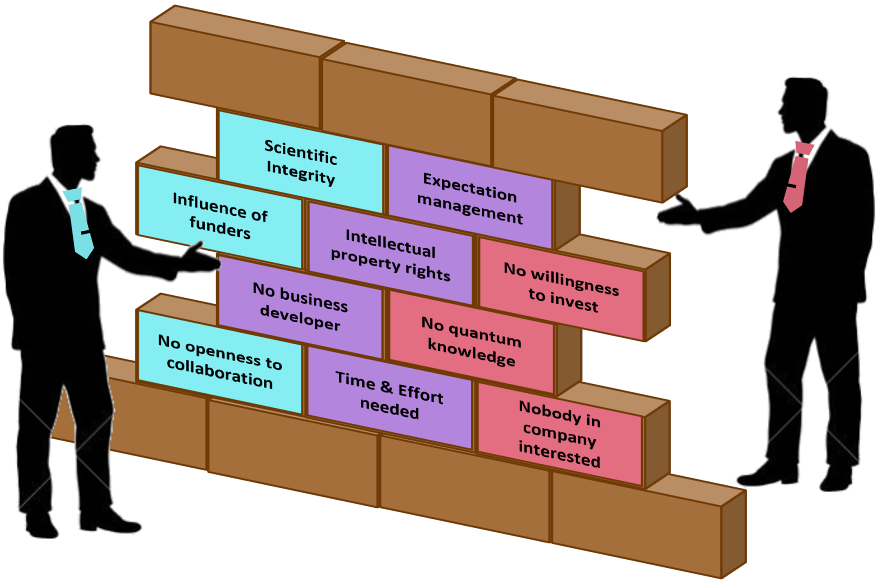


Figure 14.2: ***The wall of barriers for collaboration.*** *The brick wall with barriers with the university on one side and industry on the other. Only when all the barriers are down can they come together and collaboration becomes possible. The barriers are divided into three categories: factors that have a negative influence on the university (blue), industry (pink) and factors that are negative for both parties (purple).*

Table 14.1: ***Barriers split into categories.*** *All negative influence factors are divided into three classes: factors that have a negative influence on the university, the industry, or factors that are hindering to both parties. They are also divided according to their type: motivation, functional or organization.*

Type of factors	**University**	**Mutual**	**Industry**
Motivation	Scientific integrity	No business developer	No willingness to invest
Functional	Influence of funders	Intellectual property rights Time & effort needed	No quantum knowledge
Organization	No openness to collaboration	Expectation management	Nobody in company interested

In the Table 14.1, the factors are also divided into three classes, in addition to the division to which stakeholder they belong. These classes are motivational factors, functional factors and organizational factors and are based on the article of Stokols et al. [152]. In this article, they describe six categories of factors (Interpersonal, Organizational, Technologic, Physical Environmental, and Societal and Political) 'that either enhance or hinder the effectiveness of collaborations' [152]. Based on these six factors and emphasizing the fact that the factors belong to organizations and therefore personal motivations are not considered (see Chapter 11), the three classes could be formed. The interpersonal and intrapersonal categories of Stokols et al. are merged into the motivational class, the physical environmental, technologic, and societal and political categories form the functional class, and the organizational class remains unchanged. This allocation is established to create a clearer overview of the barriers in the situation of collaborations in the field of quantum technologies.

The class motivational factors include all barriers related to the motivation to collaborate. For the university, the most important motivational barrier is scientific integrity. Since all university research must comply with scientific integrity guidelines [153], this can be an important motivational barrier to collaborating with industry. There is a different motivating barrier for the industry, which is the willingness to invest in a technology of which it is still uncertain what it will ultimately look like. Industrial partners must dare to invest money in the development of a new technology, so without that willingness the collaboration cannot take place. A mutual motivation barrier is the need for someone, a so-called business developer, who understands both parties. This business developer can bring the parties together and find a good click on the subject of collaboration to start the collaboration. The absence of this business developer hinders the start of the collaboration.

The next class contains the functional factors for collaboration. For universities in particular, a functional obstacle is the influence of funders on the research being carried out. The university can only do research in the field of quantum technologies if it has money to pay the researchers and the necessary equipment. The money has to come from funders. When getting money, the funder has certain expectations of the results of the research. Therefore, if money is only given for certain results, it can affect the research being done. There must be clear agreements between the funders and the research about the independence of the research that can be done. Subsequently, intellectual property rights should also be part of the agreements. Both parties have an interest in the results of the development of new technologies. Universities want to produce papers on them, in order to advance the scientific community. On the other hand, industry wants to patent the results, to commercialize them and make a saleable product out of them. Before a collaboration can start, intellectual property rights must therefore be discussed in order to avoid conflicts later on. In the functional class, also, the industry has a specific barrier that only counts for them. For collaborations on the development of quantum technologies, having a certain amount of knowledge about quantum is needed. Although the industry gathers some knowledge in the phase of accepting the quantum technology, more knowledge about it is needed if you really want to do something with it. So, industry has to think about the things they do not know and reach out to universities to close these knowledge gaps. With the closing of the knowledge gap, the start of working together comes closer. Besides, both universities and business need to make time and money available to initiate collaboration. If there is only the will, but no functional matters such as time and effort, collaboration will not become reality.

The organizational factors form the last class. To be able to enter into a collaboration with an external partner, the organization must overcome the negative factors in order to be ready for them. For industry, this means that employees who are interested in quantum are needed. If those people are missing and nobody wants to get involved, the collaboration will not happen. At the university, the organizational structure must be such that collaboration with industry is encouraged. At QuTech, part of the mission is collaboration with industry, so there is no such barrier. But other universities with an organizational structure that encourages collaboration less have a harder time. A mutual negative influence factor of the organization is the expectation management that has to be done in order to have a successful collaboration. Universities and industry are likely to have different expectations of the collaboration in terms of time schedules, money, results, etc. If these expectations are not discussed in advance, major problems may arise in the process of developing quantum technology. Therefore, the management of expectations must be done from the beginning so that everyone is on the same page.

14.2.4 Overcoming barriers

Overcoming all barriers and breaking down the whole wall is quite a job to do. Fortunately, not all of this is necessary to be able to start working together. Some barriers need to be partially resolved in order to be called overcome, some barriers really need to be overcome before collaboration can be established, while others can be resolved before the collaboration begins to function in practice.

Starting with defining when a barrier has been overcome. It differs per barrier whether there must be a solution to the entire problem, or whether a partial solution will work at the start. Such as, is it a precondition for the collaboration to come about, or is it more of a balancing act on that issue before the collaboration can begin. For each barrier it will be discussed when it has been overcome well enough for the collaboration to start and when in the process it must be resolved.

No quantum knowledge
To begin with, the barrier of no quantum knowledge in companies does not have to be completely solved

before a collaboration is started. Completely solving it would mean that the company does have a lot of quantum knowledge, which is not needed at the start. After all, in this case the collaboration can also help in acquiring this knowledge. But it is important that the company has some kind of basis in quantum knowledge.

The beginning of the knowledge is gained in the phase of transition from quantum awareness to quantum acceptance, but more is needed to be ready as a company to actually start working with it. This can be done through more knowledge transfer activities. While this could be done passively as in the step towards quantum acceptance, the industry now needs to actively seek it out. Business partners can, for example, go to a conference on quantum technologies, use the Quantum for Business initiative [151] or invite researchers from universities to come and talk about the possibilities of quantum technologies for their company. For this to happen, universities must be open and give their time to invest in these companies that are willing to reach out for collaboration. Creating the intention to want more knowledge also creates the momentum to seek partnerships and thus actively think about using quantum technology in their business. So this barrier can be stated as overcome, when the company has some knowledge about quantum, but more importantly, has an idea about what they want to do with it in their business.

Nobody in company interested
Converting the barrier of 'no one in the company interested' into 'everyone in the company interested' is an impossible task to accomplish before the collaboration starts. This is another barrier where it is enough that a few people in the company get excited about working on quantum to set up a collaboration. Although a few people are enough, these few people should not just be in the lower ranks of the company's hierarchy. In that case, it is important that a manager in the higher layer is also convinced to make it work. It is best if several people in different layers of the company are interested, because then effective collaboration can be established. This barrier is also a precondition for a collaboration to be created.

It is unreasonable to force people to become interested in order to enter into a collaboration. People's enthusiasm for quantum in industry must be triggered in some other way. This 'preference' for quantum can be found in Lavidge & Steiner's hierarchy model of effects [148]. After becoming aware of the technology, and gaining knowledge about it in the step to quantum acceptance in Figure 14.1, the hierarchy of effects model describes liking and gaining preference as the next steps. The idea of the liking step is that people become interested in and feel positive about the technology. In order to get the liking of the technology, it is important that the interested people shift their attention from other technologies to quantum technologies. This can be achieved with the help of universities. If universities highlight the advantages of the technology, including its unique selling points, this can be the push that industry people need to dare to take the step from accepting the technology to actually becoming enthusiastic about it. The interest and enthusiasm must be present in at least some people in the company in order to overcome this barrier.

No openness to collaboration
For universities, if there is no openness to collaboration, it becomes very difficult to establish collaboration. But, if there is a part of the university or the mission of the university that is open to exploring what is possible with collaboration, this barrier is overcome well enough to start one.

Since this openness to collaboration is a university-wide mission, it is difficult to change it easily. However, there is increasing pressure on universities to be the engine of economic growth, which often means establishing partnerships with industry [117]. If the university's quantum department feels that those collaborations are necessary, as QuTech does [34], the openness to those collaborations increases. This barrier is an organizational issue that needs to be discussed university-wide, but can be pushed by a department to get higher on the agenda and get support to start those collaborations to create societal impact.

No business developer
Without a business developer from the university or industry, it becomes difficult to make the connection to start a collaboration. It may be possible to set up a collaboration without a business developer if both the university side and the industry side have people who are enthusiastic about working together

and have their own direct connections. When this enthusiasm or direct connection is lacking, a business developer is needed to get the collaboration going.

The most logical thing is if this business developer comes from the university, with knowledge of the industry, as universities are currently more willing to collaborate than industry. So the industry has to be convinced by this business developer to make a collaboration. It is quite a job to find such a business developer. He has to know how the industry works, but also where the entrances are in the companies for the introduction of a new technology. On the other hand, this business developer must be interested in quantum and preferably also know some of the basic theories behind the technologies. This knowledge can be trained, and does not need to be in-depth. The reason for this is that the industry does not have in-depth quantum knowledge either. So the conversation about getting the company interested in the technology would initially take place at a low level, more on management level implementations.

Seeking and attracting industry developers in quantum technologies should be high on the agenda of universities seeking to establish partnerships with industry. They should focus on attracting people who can form the bridge between universities and industry, so that collaboration in the development of new quantum technologies can begin.

No willingness to invest

The barrier of no willingness to invest in the industry is a difficult one. Investment in this case can be financing, but it also has to do with the barrier of the time and effort required. The decision-makers in the company must be convinced that it is worthwhile investing money in the development of quantum technologies. The conviction theory is formulated for making decisions in situations where the future is uncertain, as in the case of quantum [154]. It states that persuasion requires focusing on four processes: explanation, simulation, affective evaluation and communication. The quantum case provides an example of how these four processes can be used to persuade to invest in the development of quantum technology: The explanation part involves imposing the structure on the data to create understanding. This means that through knowledge transfer, such as presentations or lectures, it must be made clear to industry what is meant by quantum mechanics and how it can be transformed from a theory to practice. The simulation part is the tricky one, because here one tries to give examples of the future. The best way to do simulation is to make proof of concepts of practical applications, and this is best done in collaboration with industry. So when the frontrunner companies create such a proof of concept, more companies are likely to follow. Affective evaluation is about playing with the emotions to assess their desirability. In quantum, this can be done by using the hype around the potential of the technology. This must be done carefully, so as not to create false promises. Finally, communication is the process of organizing action through persuasion and reasoning, and spreading stories across social networks. This can be translated into the active ways of transferring knowledge from universities to industry, even at events where quantum is not the main focus, thus reaching new audiences.

The willingness to invest is another barrier that counts as a prerequisite for entering into a collaboration. As described in Section 13.1.1, doing research in quantum technologies is expensive. In the proposal for the National Growth Fund, Quantum Delta NL describes how much money they need to develop a successful quantum ecosystem in the Netherlands [35]. They expect to need €3.6 billion in 7 years from both public and private investments for the development and growth of quantum technologies. They have received €615 million from the Dutch government, so most of the remaining €3 billion must come from private investment. For that to happen, industry has to be convinced to help invest, which is also to their own advantage. Funding must come from companies that have accepted that quantum technologies will play a (big) role in the future, and the sooner they start investing and working on it, the better the position they will create for themselves on the market.

Time & Effort needed

The 'time & effort' barrier is one with soft limits when it comes to when it is enough to overcome it. As with any new thing, nothing will happen unless time and effort is put into researching what it is and how it can be made useful for the company or for the university. Like the example Lawrence Gasman gave: “You have to be serious about it. If you are not prepared to put the time and money in, nothing will happen.”.

It is also a barrier, which is not a strict condition to be met before the start, but rather a condition required from both parties during the collaboration. How much time and effort is needed for the collaboration to be successful must be discussed before the start of the collaboration, as this must be balanced between the two parties. Both the universities and the industry must invest time and effort in order to be able to do the research, find new applications and hopefully make them applicable in practice. If the time and effort is not put in, it will take forever to develop the new applications, and someone will catch up with you. The exact amount of time and effort needed to be put in, differs per project.

The barriers described above can be overcome by having a partial solution for them. For the other barriers, like the one of Time & Effort, a complete solution must be found before a successful collaboration can be established. This can usually be done by drawing up an agreement on what the collaboration will look like before it starts. In this agreement, the scientific integrity of the universities should be laid down, as well as the influence of the funders on the research to be carried out, the intellectual property rights of all parties involved and the expectations that the stakeholders have of the collaboration. If these matters are not discussed beforehand, they can later have a major impact on how the collaboration proceeds, from irritations arising from different expectations to legal issues about intellectual property. This is undesirable and so these barriers must be fully overcome, with the help of agreements, before the collaboration can begin.

Scientific Integrity
Every university has a code of conduct, which contains the guidelines for the researcher to do his job. These guidelines form the basis of integrity in research, and are based on the principles of honesty, transparency, scrupulousness, responsibility and independence [153]. The guidelines in the code of conduct must also be observed when working with industry. This means that in the agreement that is concluded about the collaboration, these guidelines must be kept next to it, and all agreements must comply with them.

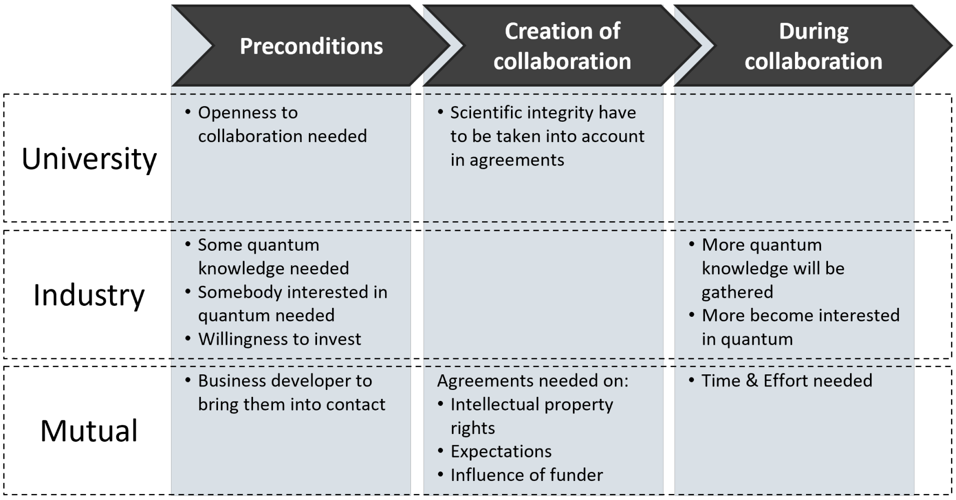
These guidelines are important for the scientific community and scientific research. They are intended to prevent research misconduct, which is defined as falsification, fabrication, or plagiarism in any form of research results. Industry does not normally have to comply with these guidelines on research integrity, but when it collaborates with universities, it has to comply with them. This may mean that the 'normal' way of working in the company is not possible, and that processes have to be adapted. Therefore, it is important to take the guidelines for scientific integrity seriously and to take them into account when drawing up the agreements for the collaborations.

Intellectual property rights
Another barrier to be dealt with in an agreement between universities and industry is intellectual property rights. Having this agreement in place is a precondition for starting the actual collaboration. Coming to this agreement means a lot of prior discussion about the form and goals of the collaboration. Both parties have to think about how they want to arrange their intellectual property rights and how they want to divide those rights between them. What are they going to do when they have developed a new working technology? Are they going to publish an article about it? Or will they patent the technology first? Etc? Both universities and industry have their own preferences, and together they must find a compromise. Until there is an agreement on how to deal with the rights, the collaboration cannot begin. At least, that would be a very inconvenient thing to do.

Expectation Management
As with intellectual property rights, the expectations of both parties must be managed in advance. Ingrid Romijn explained: "I notice this now in collaborative projects that we do with companies. They have a different pace, a different expectation pattern, and they expect, if you say we are going to work on this and this, that there will be results after three months. So that is something you have to be very clear about to the companies." The same applies, of course, to the expectations that universities have towards the business community. This means that agreements must be made about the expectations, but also about the time effort of both parties, before the collaboration can start.

The business developer can play a role in drawing up these agreements, because he can mediate between the two parties. Each party has its own wishes and requirements, and a compromise must be reached to find a common ground for setting up the collaboration. Finding a balance between universities and industry can be very difficult, as they also have their own internal rules. The business developer can act as a third party to ensure that an agreement is reached that is acceptable to all.

Influence of funders
Funding for the research mainly carried out at universities, without anything in return, almost never comes from the private sector. As a result, the influence of funders on the research conducted is something to be taken seriously; the scientific integrity of the work must not be compromised. This means that in addition to discussions and agreements on intellectual property rights and expectation management, both parties must also consider the influence they have on the outcome of the research. If industry only gives money for certain results, this may influence the research done at the university, but also the collaborative research between the two. So clear agreements must be made between universities and industry about the independence of the research that can be done.



	Preconditions	Creation of collaboration	During collaboration
University	• Openness to collaboration needed	• Scientific integrity have to be taken into account in agreements	
Industry	• Some quantum knowledge needed • Somebody interested in quantum needed • Willingness to invest		• More quantum knowledge will be gathered • More become interested in quantum
Mutual	• Business developer to bring them into contact	Agreements needed on: • Intellectual property rights • Expectations • Influence of funder	• Time & Effort needed

Figure 14.3: ***The timeline of overcoming barriers.*** *Not all barriers need to be (fully) resolved before collaboration can take place. In addition to the degree of solvability, the moment differs for each barrier. Some must be resolved at the start, others can be resolved just before the actual collaboration begins or even during the collaboration.*

Some barriers, such as no openness to collaboration, no quantum knowledge, no one in the company interested, no willingness to invest or no business developer, need to be (partially) resolved before the establishment of a collaboration between universities and business in the development of quantum applications can be considered. Once the decision has been made to set up a collaboration, the barriers of scientific integrity, intellectual property rights, influence of funders and expectations have to be overcome before the actual collaboration can start. During the collaboration, time & effort stays needed to make the collaboration successful. This overview is given in Figure 14.3.

Thus, not every barrier needs to be completely overcome before collaboration can begin. For several barriers, it is enough to partially resolve the issue to be far enough along to establish collaboration. Others must be completely resolved in order to establish a successful collaboration. Some barriers must be resolved before the start, just before the actual collaboration begins.

14.3 Conclusion

This chapter combines the results of the previous sub-questions and the interviewees' vision of the future, to create the vision of the next steps for how universities and industry can work together.

It has become clear that knowledge about quantum is necessary to start developing new technologies. Universities currently have the most knowledge about quantum, while industry lacks this knowledge. This imbalance leads to a situation of technology-push, which is an undesirable situation. Industry must therefore be involved in the development of quantum technologies. However, before having sufficient knowledge and being ready to enter into partnerships to work on quantum, two other steps need to be taken.

The first step in entering into a collaboration on quantum technologies is for the industrial party to become aware of the existence of quantum and how quantum can play a role in the industry. If one is not aware of the existence of a technology, it becomes very difficult to get started. The second step is to accept the arrival of quantum technologies. This can be done through knowledge transfer activities or the transfer of university graduates and staff to positions in industry. Once the acceptance of quantum is there, the step can be taken to actually work on it and make it applicable, as can be seen in Figure 14.1.

The steps of awareness, acceptance and collaboration find their basis in the theory of the hierarchy of effects [148] and the AAAM [150]. The model of the next steps in collaboration applies those ideas to collaboration in the development of quantum technology, which forms a staircase with three steps to take.

The last step, from acceptance to collaboration, is the most difficult. The positive influencing factors are the driving forces to set up those collaborations, but the negative influencing factors are barriers to doing so. The barriers are divided into three categories, those that have a negative influence on the university, those that have a negative influence on industry, and those that have a mutual negative influence.

In addition to these categories, the barriers can also be classified into three classes: motivational factors, functional factors and organisational factors. This classification was made based on Stokols et al. [152], where factors were defined as those factors 'that hinder the effectiveness of collaborative relationships'.

It is not necessary to remove all barriers before starting to establish a collaboration. Some barriers need to be (partially) resolved in order to start the creation of the collaboration, while others can be resolved before collaboration begins to function in practice. It varies from barrier to barrier whether there must be a solution to the whole problem, or whether a partial solution will work in the beginning. Such as, is the barrier a precondition for the collaboration to come about, or is it more of a balancing act on that issue before the collaboration can begin.

In Figure 14.3 on overview is given of all barriers on the timeline in setting up the collaboration between industry and universities. What becomes clear is that the barriers of scientific integrity, intellectual property rights, influence of funders and expectations have to be overcome completely before the actual collaboration can start. This needs to be done by making agreements on it. The other barriers are either a precondition, which means they need to be solved beforehand, or are developing during the collaboration.

Chapter 15

Conclusion

The aim of the work was to develop a vision on industry-university collaboration in the development of quantum technology. This vision contains the detailed stakeholders, purpose, type, and influence factors that an industry-university collaboration must meet. In addition to these aspects, a three-step model could be drawn up for setting up these collaborations. These steps are based on the conceived stakeholders, purpose, type, and influence factors of industrial-university collaboration, the status of the current situation and the future vision of the interviewees.

Stakeholders
By examining all parties involved in the development of quantum technologies, an overview of all stakeholders is created. The most important stakeholders are the universities and industry, whereby of the latter, the most potential lies with the large companies. These large companies do not have the knowledge and expertise about quantum technology, but they do have the financial capabilities to invest in R&D.

In fact, not every large company is suitable. The best potential companies to collaborate with universities on quantum technologies are those operating in a sector most likely to be affected first by quantum. Based on the quantum technology being developed, the sector differs from the industry. Quantum sensors are most likely to affect the military and aerospace sectors, for quantum networks it is the telecommunications and financial sectors, and for quantum computers it is the companies active in high-performance computing, medicine, the energy sector, the automotive industry or data security.

Purpose
After analysing the literature and the findings from the interviews, it appears that the answer to the question 'What should be the purpose of collaboration between universities and industry in the quantum technology?' has two sides. For the university, the main objectives should be to commercialize research ideas and to test their potential in society & to create new knowledge faster and to move towards a knowledge-based economy. For industry, the main reason for partnering with universities should be to economically capture useful knowledge to gain a competitive advantage, & access to advanced research knowledge and infrastructure to grow their business.

Type
The purpose of the collaboration has laid the foundation for what the collaboration should look like. The next step is to determine which form of collaboration is most suitable for the development of quantum technology. Interactions such as the sharing of facilities, participation in knowledge transfer activities and the transfer of university graduates and staff to positions in industry are applicable in the field of quantum development, but can be seen more as a basis. According to the interviews, the type of collaboration that is most effective and has the greatest impact is the implementation of joint R&D projects between universities and industry. This type of collaboration promises to produce applicable technologies that can be used in practice.

Influence factors

The establishment of a collaboration is influenced by many different factors. A division is made between factors that influence the collaborations positively and factors that have a negative influence. In addition to the split into positive and negative, all influencing factors were categorized according to whether the factor exists from a university perspective, from an industry perspective or whether the factor applies to both.

Positive influence factors are, for example, making the transition from research laboratory to prototypes, obtaining funding, making economic impact, learning the possibilities of new technologies or obtaining PR value. Examples of negative influence factors are scientific integrity, influence on research results, intellectual property rights, the unwillingness to invest in something uncertain, expectation management and the time and effort needed to build relationships.

Next steps

When the interviewees were asked how the collaboration between business and universities should be set up, they believe that the universities should take the lead. The reason for this is that they have more knowledge and insights on how this should be done. They can select the most potential companies in preferred sectors to set up proof of concepts with. Industry must enter into these collaborations because they cannot be left behind. Quantum technologies are coming and will change the field, so it is better for them to start investing now than to wait and be late. Some companies already see this and have started doing so, but many have not done much yet.

All input found in the literature and emerging from the interviews has been used to draw up a three-step model for establishing collaborations in the field of quantum technology. The first step of this model is awareness of the existence of quantum and what quantum can mean for industry. Most companies know that quantum exists, but have no idea of its possible consequences for their field. If universities provide them with information on this subject, companies can become aware of the existence of quantum. These knowledge transfer activities are the driving forces to take a company from awareness of the existence of the technology to its acceptance.

This acceptance is important because it lays the initial foundation on which collaborations can be built. This basis is already too thin to immediately start with a joint R&D project of universities and industry in the field of quantum technologies. To move from awareness to actual work, a big step is needed. The driving forces of this step are the positive influencing factors of a collaboration, but the negative influencing factors are hindering factors.

Those hindering factors act as barriers between universities and industry and are holding them back. They must be overcome one by one. Some of these barriers apply only to universities, others only to business, or to both. There are three types of barriers, namely motivational, functional and organizational. Only when all barriers are overcome is the way clear for a possible successful collaboration.

It is not necessary to remove all barriers before starting to establish a collaboration. Some barriers need to be (partially) resolved in order to start the creation of the collaboration, while others can be resolved before collaboration begins to function in practice. It varies from barrier to barrier whether there must be a solution to the whole problem, or whether a partial solution will work in the beginning. Such as, is the barrier a precondition for the collaboration to come about, or is it more of a balancing act on that issue before the collaboration can begin.

Vision

To return to the main objective of the research, 'What should be the vision for collaboration between industry and universities in the development of quantum technology?'. The vision consists of several elements that should lay the foundation for the collaborations in the field of quantum development. Universities and industry (mainly large companies) should aim to work together. For the universities, the goal should be based on their will to commercialize research ideas and test their potential in society, as they want to create new knowledge faster and move towards a knowledge-based economy. For business, the goal should be to capture useful knowledge economically in order to gain a competitive advantage and to gain access to advanced research knowledge and infrastructure to grow their business. Joint R&D

projects are best suited to achieving these goals. They promise to deliver applicable technologies that can be used by industry in practice. The main drivers for this collaboration are funding, the high technical level of the partners, faster creation of useful applications, high PR value and creation of economic impact. The barriers to such collaboration are scientific integrity, influence on research results, intellectual property rights, reluctance to invest in something uncertain, expectation management and the time and effort required to build relationships.

In order to create these collaborations, universities must take the lead. When industry is aware of the existence of quantum technology, knowledge transfer activities between universities and industry should teach them more about quantum and what quantum can mean for their industry. This knowledge brings companies to a level of quantum acceptance. The drivers of collaboration compel companies to enter into partnerships with universities, but there are some barriers that must first be overcome. Some of these barriers are preconditions that must be met before further consideration can be given to entering into a collaboration. These are, for example, having the willingness to invest, having someone interested in the company, but also the university must be open to collaboration. If these conditions are met, universities and business must make agreements about scientific integrity, intellectual property rights, influence of funders and expectations. Only when these agreements have been made, joint R&D collaborations can be launched successfully.

Establishing collaboration between universities and industry in the development of quantum technologies is as difficult as generating entanglement with the smallest particles. Both parties have to communicate a lot to get to a state where they are on the same wavelength. This requires a lot of hard work, but when the effort pays off and the entanglement comes about, the collaboration has a great chance of success.

Chapter 16

Discussion and outlook

In the process of finding answers to the sub-questions and determining the vision on collaboration, some things went well, while other things could use some refinement for a next time. This chapter discusses the research conducted and its results, naming the good points, the room for improvement and the things that could be done in a follow-up research. This is done by going through each chapter and at the end discussing the social relevance of the work.

16.1 Methods

The research approach followed consisted of different steps. Each step has its own objectives, its own way of working, and is used to gain different insights into the collaboration between university and industry in the development of quantum technology. A linear approach, with some parallel steps, was chosen for this research. This was done because the results of a step serve as a basis for the next step. This made it a logical choice to do this linearly and not in a feedback loop.

The narrative literature review was done to gain insight into current knowledge on university-industry collaborations and how to collaborate in general, but also on the history of quantum, what has been done, what is happening now, etc. This overview was done structurally, with a defined search field, but also not sticking to the first search terms and snowballing into more relevant articles. This resulted in an overview of aspects that are important in collaboration, which helped to form the basis of literature for the various sub-questions. Without this narrative literature review, these aspects will not be clear, and it would have been more difficult to find the relevant literature to answer the sub-questions.

A semi-structured interview protocol was used for the interviews. This had the advantage that the interviews flowed smoothly and created a conversation rather than just a series of questions to be answered. This also caused some directions in the conversations that were not anticipated in advance, but were great insights into the situation of quantum development. The downside was that sometimes these side paths were not useful at all and only took up time. The interview protocol itself was based on the categories of the sub-questions and the concepts that belonged to these categories. This was very useful in the interviews, as it was easy to oversee which concepts had already been discussed and which had not.

One of the reasons for choosing to look at collaborations within quantum technology from a primarily university perspective is that most of the people working on it are employed by universities. These people were very open to discuss how they view these collaborations. It was very difficult to find people from companies who wanted to share their views. The main point here is that it is difficult to say anything meaningful about it if your company is not yet involved in quantum. The companies that have already started working together do not want to share all the inside information, because they now have a leading position that they do not want to give up. Therefore, the interviews were conducted with people with a university perspective on collaborations in the development of quantum technology.

The choice of interviewees, four of the five working in the Netherlands, also leads to a vision that will work mainly in the Netherlands and perhaps in the rest of Europe. In the interviews, it became clear that the way of working between the US and the Netherlands is very different, especially in terms of who is in charge of developing new technologies. In the US, it is the large companies, whereas in Europe it is mainly the universities. Therefore, the results of this research are probably most effectively applicable in the Netherlands, and perhaps other European countries with a similar way of working.

16.2 Stakeholders

The stakeholders of university-industry collaborations are not specific or applicable only in the case of quantum technology development. The structure of the stakeholders, who usually act as funders of the development, can also be outlined in the same way as for other technologies.

The special feature of quantum technology is the distribution of potential industry sectors for development. The distribution is based on the different directions of quantum technology, making it unique to this technology. The fact that many different sectors will potentially be affected by quantum technology is also unique compared to other technologies. These usually have a more defined direction of sectors where the technology will be applied first.

16.3 Purpose

Finding the purpose of the collaboration between universities and industry in the development of new quantum technologies was a difficult matter. The general goals of collaborations are, as the name suggests, very general. The goal specific to quantum is difficult to discern. Primary and secondary motivations also influence the purpose of collaboration. It is difficult to look inside the organizations to find their primary and secondary motivations. Even the employees of those organizations have an idea, but do not have a complete picture of the motivations.

For further research on these collaborations, more attention should be paid to discussing the motivations within the organizations and finding the deeper layers of why they want (or do not want) to engage in the development of quantum technologies and what are the motivations behind engaging in collaborations with other parties in this field. The latter is also interesting when placed in perspective with developing the new technologies themselves.

16.4 Type of collaboration

In terms of the type of collaboration, there were many options. These options were divided into three categories, based on the degree of relational involvement in the collaboration. Very general forms of interaction could be found in the literature. These could be narrowed down to interactions between universities and industry. Although this gave a clearer overview, there were still many possibilities. Using the answer given in the interviews, it became clear that the most effective ways of interacting are those with a high relational commitment. These ways cost the most time and effort, but also lead to the most practical applications. This conclusion could apply to any new technology. What makes quantum special is that what those practical applications should look like has yet to be discovered, and there are no other concepts with which they are comparable. This makes collaborative R&D projects to build proof of concepts the most suitable for the development of new quantum technologies.

16.5 Influence factors

For the factors influencing the (formation of) collaboration, theories on collaborations and the findings from the interviews were examined. This gave an overview of all the influencing factors, both positive and negative, for collaborations in the field of quantum. This summary can be expanded in future research by also looking at the factors that influence collaborations in other 'new' technologies such as nanotechnology, genetic modification or synthetic biology. Using the influencing factors from those technologies, a comparison can be made with quantum and which factors might play a role in future development and collaboration.

16.6 Next steps

To determine the next steps in the development of quantum technology, the results from the literature and the interviews were combined. This led to the three-step model, going from awareness to collaboration via acceptance. This model found its basis in other social science theories and could be made applicable to the field of quantum. It focuses on what the steps are and what is needed to get from one step to the next. That was the purpose of the research, so that requirement has been met.

For future research, these steps could be explored in more depth. This means that the steps are still quite theoretical about what they mean or how they should be fulfilled. In order to make the vision more practically applicable, each step should be examined to see what is needed in practice to bring the industry to this step. So there should be more of a roadmap with very practical measures on how the steps will be taken. For example, when talking about the need for knowledge transfer activities to bring companies from quantum awareness to quantum acceptance, only the need is mentioned. But adding which knowledge transfer activities these should be specifically, or even better having a name and date of these activities and who should speak and which companies should be convinced, would make the vision a lot more practical.

In addition to making the steps more practical, overcoming the barriers can be made more concrete in future research. For each barrier, an idea is now given of how it can be overcome, but no concrete actions are described. To do this, more needs to be known about the specific stakeholders and their situation. For example, if QuTech is interested in setting up a collaboration with a potential industry partner, it can use the wall of barriers to identify where the obstacles are. Based on the situation of the industry partner, i.e., which barriers exist and which ones have already been resolved, a plan can be made to overcome the remaining barriers and start the collaboration.

16.7 Conclusion

The purpose, type and influence factors of collaborations between universities and industry in the development of quantum technology are determined in this research. Based on this, a vision for those collaborations is developed. What needs to be investigated in future research is how these findings will be shared with the relevant stakeholders, and whether they agree with the stated purpose, type and influence factors. It is a good start for building a collaboration, but how do you communicate it to parties who are not yet familiar with the technology, and how do you persuade them?

16.8 Social Relevance

This research is conducted to create a vision for industry-university collaboration in the development of quantum technology, with a focus on how industry can be involved in the development. The reasoning behind creating this vision is that much research has been done on university-industry collaborations, on how they work, what the goals and motivations are or how they interact. What was missing was the application of this research to how to set up new collaborations, specifically in the field of quantum.
Quantum is a relatively young field of research, with a unique starting point. As theory is transformed into practical applications, while it is still uncertain whether that will work at all. This uncertainty, combined with the great promises of quantum technologies, leads to a unique situation where it is very difficult to predict what the impact of quantum will be in universities and industry in the future.

Looking at stakeholders, that structure can be applied to other new technology as well. The same is true for the literature sections on the purpose of collaboration, the type of collaboration and the positive and negative influence factors. These findings are from literature that did not focus on a specific technology or collaboration in a specific sector. This is different for the results from the interviews, as all interviewees are now working in the field of quantum. Their views and opinions have been shaped by the university environment they are in, which has a progressive attitude towards making quantum applicable.

The combination of the general literature findings, with the subjective interview results, form the results on the sub-questions. Together with the basis of the interviewees' current situation and visions for the future, these results are used to formulate the step-by-step vision for establishing collaborations in the field of quantum development. And although this vision is entirely focused on quantum technology, the main structure can also be used for other technologies.

As with the AAAM model [149, 150] and the hierarchy of effects [148], this step-by-step vision is not something entirely new in the social sciences. What is done in this vision is to make more practical how each step can be achieved, what drives the making of steps and what hinders this in the field of quantum. These insights, based on the results of the sub-questions, can be distilled into concepts that can be applied to any other technology. The condition must then be that the technology comes from the same background, meaning that it must be a radically new technology with great promise and no practical application yet in widespread use.

Part IV

General Conclusion

Chapter 17

Conclusion

17.1 Applied Physics

Throughout the work, the goal was to develop the physical, or hardware, layer of a quantum network stack. The first software layer of the network stack connected to the physical layer is the link layer. For entanglement-based quantum networks, the successful operation of a link layer with a physical layer is shown. The physical layer's entanglement generation procedure — implemented by using two NV center-based quantum network nodes — is abstracted by the link layer into a robust platform-independent service that can be utilized to run quantum networking applications.

This step in abstracting the use of quantum hardware is the first step in creating quantum computers that can be operated by end users who have no knowledge of quantum mechanics. The ultimate goal of the quantum computer is to develop all the software layers and ultimately applications for the quantum computer in such a way that the end-user can use it as they use their current computer. Our 'classic' computer also works with bits, made of transistors, but when you send an e-mail, you have no idea what goes on in all the software layers and hardware layers that convert your e-mail into bits, send it and transform it back again at the receiving end. Fortunately, we don't need to know, and this is exactly the procedure we want for the quantum computer.
When the technology of the quantum computer and quantum networks is further developed, the enormous computing power it possesses can be used by someone without full quantum knowledge. However, the road to such a quantum network is long. The hardware layer is now linked to the first software layer, but the hardware layer itself still only consists of two quantum bits. That is far too few to build a quantum network on. Secondly, the first software layer is now linked, but all other higher-level software layers still have to be developed and linked to the system. And the final software layer must contain all the applications that can be run by the end users, and it will take many years before these are developed and can run on real quantum bits.

So there is still much work to be done in the development of a quantum computer, but this first proof of connecting the hardware to the software and abstracting from the generation of entanglement through the link layer is the first step. Other quantum network platforms can also make use of the approaches offered here (which are not unique to our diamond devices) and this will accelerate the development of large-scale and heterogeneous quantum networks.

17.2 Communication Design for Innovation

The aim of the work was to develop a vision for university-industry collaborations in the development of quantum technology. This vision contains the detailed stakeholders, purpose, type, and influence factors that an industry-university collaboration must meet. In addition to these aspects, a step-wise model could be drawn up for setting up these collaborations. These steps are based on the conceived stakeholders, purpose, type, and influence factors of industrial-university collaboration, the status of the current situation and the future vision of the interviewees.

Given that most R&D in quantum technologies is currently carried out at universities with little involvement from industry, the vision developed may help to involve industry more. It is necessary to create a better balance between universities and industry in the development of new technologies, so that these technologies can result in applications that will be used in practice. Only in this way can the technologies be commercialized and have an economic impact.

Exactly what these collaborations should look like is unclear, but with the help of the developed vision, a better picture can be formed of their structure. What becomes clear in the vision is that the type of collaboration does matter for the speed of technological developments. With high relational involvement, the chance of developing a working proof of concept of a new practical application of quantum technology increases. In addition, there are many factors that influence the (establishment of the) collaboration. The positive factors stimulate the realization, while the negative factors act as barriers that must be overcome. Some of these barriers are more difficult to overcome, and others are sufficient to be partially resolved. Nevertheless, these barriers should be taken into account when setting up a university-industry collaboration in order to make it a success.

Exactly what collaboration between universities and industry will look like is difficult to predict, as is how quantum technologies will develop. The future of quantum is uncertain, but that it will be there in the future is something most people agree on. So if quantum has the potential to make an impact in a specific industry sector and your company is active in that sector, it is smart to jump on the moving train now. That way, you can help lay the train tracks for you and steer the technology in the way that can be most effective for your business.

17.3 Future of quantum

When the first 'classical' computer was developed, it was intended for military purposes. Being able to send text messages to each other was the first goal. When the first message was sent, they never imagined that we would all now be walking around with a small computer in our pocket and able to send messages all day long.

Although we have the example of the 'classical' computer, the future of the quantum computer cannot be predicted. Of course, there are already ideas about possible applications for when the quantum computer becomes a reality and can be used commercially, but it is expected that these applications are just the beginning and that unthinkable things will become possible with quantum technologies for the time being

Looking into the distant future is therefore unrealistic, but something more meaningful can be said in the coming years. The quantum hype will still be there, because it is expected that only more financial resources will become available to realise all the promises that quantum holds. On the other hand, the question is when this hype-bubble will burst. How long will investors find a reasonable time to develop these technologies, and when will they find that they have waited long enough, withdraw funding and start investing in something new? Nobody knows.

It also depends on the type of quantum technology that will be developed. Quantum sensors, quantum networks and quantum computers all have different timelines based on the difficulty of making them practical. These different timelines affect different industries at different times. Now is the time for industry to delve into quantum to see how far along the technology is, what the technology means to them, and how they can help develop it. If the industry, and therefore the end users, are not involved, the applications will not meet their requirements and cannot be commercialized.

So the future of quantum is unpredictable, but this is the time for integration and collaboration to enable quantum technologies to be used in future everyday life.

References

[1] A Dahlberg et al. “A link layer protocol for quantum networks”. In: *Proceedings of the ACM Special Interest Group on Data Communication* (2019). DOI: `10.1145/3341302.3342070`.

[2] H. Bernien et al. “Heralded entanglement between solid-state qubits separated by three metres”. british. In: *Nature* 497.7447 (2013), pp. 86–90. DOI: `10.1038/nature12016`.

[3] N. Kalb et al. “Entanglement distillation between solid-state quantum network nodes”. british. In: *Science* 356.6341 (2017), pp. 928–932. DOI: `10.1126/science.aan0070`.

[4] PC Humphreys et al. “Deterministic delivery of remote entanglement on a quantum network”. In: *Nature* 558.7709 (2018), pp. 268–273. DOI: `10.1038/s41586-018-0200-5`.

[5] M Pompili et al. “Realization of a multinode quantum network of remote solid-state qubits”. In: *Science* 372.6539 (2021), pp. 259–264. DOI: `10.1126/science.abg1919`.

[6] S.L.N. Hermans et al. “Qubit teleportation between non-neighboring nodes in a quantum network”. british. In: *arXiv* (2021). DOI: `arXiv:2110.11373`.

[7] S Wehner, D Elkouss, and R Hanson. “Quantum internet: A vision for the road ahead”. In: *Science* 362.6412 (2018), eaam9288. DOI: `10.1126/science.aam9288`.

[8] H. Bernien. *Control, measurement and entanglement of remote quantum spin registers in diamond.* Ph.D. thesis, Delft University of Technology. 2014. URL: `https://doi.org/10.4233/uuid:75130c37-edb5-4a34-ac2f-c156d377ca55`.

[9] W. Pfaff. *Quantum measurement and entanglement of spin quantum bits in diamond.* Ph.D. thesis, Delft University of Technology. 2013. URL: `https://doi.org/10.4233/uuid:62208a4a-72c6-45b5-af51-1a8e8f8bfdd8`.

[10] N. Kalb. *Diamond-based quantum networks with multi-qubit nodes.* Ph.D. thesis, Delft University of Technology. 2018. URL: `https://doi.org/10.4233/uuid:249753ae-9000-446a-9375-63c1e1165cc1`.

[11] B.J. Hensen. *Quantum Nonlocality with Spins in Diamond.* Ph.D. thesis, Delft University of Technology. 2016. URL: `https://doi.org/10.4233/uuid:b307dca0-79a4-4cc9-af91-a2927a61088e`.

[12] *Digging into Diamond Types.* 2017. URL: `https://4cs.gia.edu/en-us/blog/digging-diamond-types/`.

[13] S Baier et al. “Orbital and Spin Dynamics of Single Neutrally-Charged Nitrogen-Vacancy Centers in Diamond”. In: *Physical Review Letters* 125.19 (2020). DOI: `10.1103/physrevlett.125.193601`.

[14] MW Doherty et al. “The negatively charged nitrogen-vacancy centre in diamond: the electronic solution”. In: *New Journal of Physics* 13 (2011), p. 5019. DOI: `10.1088/1367-2630/13/2/025019`.

[15] MA Ali Ahmed, GA Álvarez, and D Suter. “Robustness of dynamical decoupling sequences”. In: *Physical Review A* 87.4 (2013). DOI: `10.1103/physreva.87.042309`.

[16] M.H.M.A. Abobeih. *From atomic-scale imaging to quantum fault-tolerance with spins in diamond.* Dutch. Ph.D. thesis, Delft University of Technology. 2021. URL: `https://doi.org/10.4233/uuid:cce8dbcb-cfc2-4fa2-b78b-99c803dee02d`.

[17] A. Dahlberg. *A quantum network stack?* 2019. URL: `https://blog.qutech.nl/2019/05/22/a-quantum-network-stack/`.

[18] *Computer Network - TCP/IP model.* URL: `https://www.javatpoint.com/computer-network-tcp-ip-model`.

[19] *The no-cloning theorem.* 2015. URL: `https://www.quantiki.org/wiki/no-cloning-theorem`.

[20] P Dhaker. *Introduction to SPI Interface.* 2018. URL: `https://www.analog.com/en/analog-dialogue/articles/introduction-to-spi-interface.html#`.

[21] Anne Broadbent, Joseph Fitzsimons, and Elham Kashefi. "Universal Blind Quantum Computation". british. In: *2009 50th Annual IEEE Symposium on Foundations of Computer Science* (2009). DOI: `10.1109/focs.2009.36`.

[22] M. Pompili. *Multi-Node Quantum Networks with Diamond Qubits.* Ph.D. thesis, Delft University of Technology. 2021. URL: `https://doi.org/10.4233/uuid:b125ec2d-e2af-4708-bccc-0a2357a533b1`.

[23] QInfer. *Data Analysis with QInfer.* 2012. URL: `https://nbviewer.org/github/QuinnPhys/PythonWorkshop-science/blob/master/lecture-5-qinfer.ipynb`.

[24] Christopher Granade et al. "QInfer: Statistical inference software for quantum applications". british. In: *Quantum* 1 (2017), p. 5. DOI: `10.22331/q-2017-04-25-5`.

[25] Christopher Granade, Joshua Combes, and D G Cory. "Practical Bayesian tomography". british. In: *New Journal of Physics* 18.3 (2016), p. 033024. DOI: `10.1088/1367-2630/18/3/033024`.

[26] C. E. Bradley et al. "A Ten-Qubit Solid-State Spin Register with Quantum Memory up to One Minute". british. In: *Physical Review X* 9.3 (2019). DOI: `10.1103/physrevx.9.031045`.

[27] Stephanie Wehner, David Elkouss, and Ronald Hanson. "Quantum internet: A vision for the road ahead". british. In: *Science* 362.6412 (2018), eaam9288. DOI: `10.1126/science.aam9288`.

[28] Nature Editorial. *How 'spooky' is quantum physics? The answer could be incalculable.* 2020. URL: `https://www.nature.com/articles/d41586-020-00120-6?error=cookies_not_supported&code=6fa9e7b9-0531-423d-872c-d23b4ef31dbe` (visited on 04/06/2022).

[29] 38 Aaronson. *What Makes Quantum Computing So Hard to Explain?* June 8, 2021. URL: `https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608` (visited on 04/06/2022).

[30] Quantum Delta Nederland. *Nationale Agenda Quantumtechnologie.* british. Feb. 2020. URL: `https://www.rijksoverheid.nl/documenten/brochures/2020/02/17/nationale-agenda-quantumtechnologie`.

[31] *QuTech - Research institute for quantum computing and quantum internet.* Feb. 9, 2022. URL: `https://qutech.nl/` (visited on 04/06/2022).

[32] *Intel en QuTech leveren eerste industrieel geproduceerde qubit.* Dutch. Apr. 4, 2022. URL: `https://www.tudelft.nl/2022/tu-delft/intel-en-qutech-leveren-eerste-industrieel-geproduceerde-qubit` (visited on 04/08/2022).

[33] Heera Dijk. *Collaboration Microsoft and TU Delft started.* June 1, 2017. URL: `https://qutech.nl/2017/06/01/microsoft-and-tu-delft-collaboration-started/` (visited on 04/12/2022).

[34] Qdnl. *Community Achievements.* british. Apr. 6, 2022. URL: `https://quantumdelta.nl/` (visited on 04/06/2022).

[35] Quantum Delta Nederland. *Projectvoorstel voor het Nationaal Groeifonds.* british. Feb. 2021. URL: `https://quantumdelta.nl/pdf/QDNL_final_1feb.pdf`.

[36] QuTech. *Quantum Delta NL awarded 615 million euro from Netherlands' National Growth Fund to accelerate quantum technology.* Apr. 14, 2021. URL: `https://qutech.nl/2021/04/09/quantum-delta-nl-awarded-615-million-euro-from-netherlands-national-growth-fund-to-accelerate-quantum-technology/` (visited on 03/14/2022).

[37] Maarten C.A. van der Sanden and Frans J. Meijman. "Dialogue guides awareness and understanding of science: an essay on different goals of dialogue leading to different science communication approaches". british. In: *Public Understanding of Science* 17.1 (2008), pp. 89–103. DOI: `10.1177/0963662506067376`.

[38] Frans van Dam et al. “Science Communication”. british. In: *World Scientific Publishing Co. Pte Ltd* (2020). DOI: `10.1142/11541`.

[39] Mark S. Reed. “Stakeholder participation for environmental management: A literature review”. british. In: *Biological Conservation* 141.10 (2008), pp. 2417–2431. DOI: `10.1016/j.biocon.2008.07.014`.

[40] Meinsma. *Demystifying the quantum internet.* Apr. 2021.

[41] Giada Di Stefano, Alfonso Gambardella, and Gianmario Verona. “Technology push and demand pull perspectives in innovation studies: Current findings and future research directions”. british. In: *Research Policy* 41.8 (2012), pp. 1283–1295. DOI: `10.1016/j.respol.2012.03.021`.

[42] Jan van den Ende and Wilfred Dolfsma. “Technology-push, demand-pull and the shaping of technological paradigms - Patterns in the development of computing technology”. british. In: *Journal of Evolutionary Economics* 15.1 (2005), pp. 83–99. DOI: `10.1007/s00191-004-0220-1`.

[43] David Mowery and Nathan Rosenberg. “The influence of market demand upon innovation: A critical review of some recent empirical studies”. british. In: *Research Policy* 22.2 (1993), pp. 107–108. DOI: `10.1016/0048-7333(93)90051-i`.

[44] Cambridge Dictionary. *collaboration definition: 1. the situation of two or more people working together to create or achieve the same thing: 2.... Learn more.* May 18, 2022. URL: `https://dictionary.cambridge.org/dictionary/english/collaboration` (visited on 05/24/2022).

[45] TU Delft. *Communication Design for Innovation (CDI).* Dutch. 2021. URL: `https://www.tudelft.nl/tnw/over-faculteit/afdelingen/science-education-and-communication/communication-design-for-innovation-cdi` (visited on 05/24/2022).

[46] Marco Galvagno and Daniele Dalli. “Theory of value co-creation: a systematic literature review”. british. In: *Managing Service Quality* 24.6 (2014). Ed. by Evert Gummesson, Cristina Mele, and Francesco Polese, pp. 643–683. DOI: `10.1108/msq-09-2013-0187`.

[47] Per Kristensson, Jonas Matthing, and Niklas Johansson. “Key strategies for the successful involvement of customers in the co-creation of new technology-based services”. british. In: *International Journal of Service Industry Management* 19.4 (2008), pp. 474–491. DOI: `10.1108/09564230810891914`.

[48] Stephen Biggs and Grant Smith. “Beyond methodologies: Coalition-building for participatory technology development”. british. In: *World Development* 26.2 (1998), pp. 239–248. DOI: `10.1016/s0305-750x(97)10041-9`.

[49] Ronald Batenburg and Roel Rutten. “Managing innovation in regional supply networks: a Dutch case of “knowledge industry clustering””. british. In: *Supply Chain Management: An International Journal* 8.3 (2003), pp. 263–270. DOI: `10.1108/13598540310484654`.

[50] Iñaki Peña. “Knowledge networks as part of an integrated knowledge management approach”. british. In: *Journal of Knowledge Management* 6.5 (2002), pp. 469–478. DOI: `10.1108/13673270210450423`.

[51] Diane H. Sonnenwald. “Scientific collaboration”. british. In: *Annual Review of Information Science and Technology* 41.1 (2007), pp. 643–681. DOI: `10.1002/aris.2007.1440410121`.

[52] Christopher S. Hayter, Einar Rasmussen, and Jacob H. Rooksby. “Beyond formal university technology transfer: innovative pathways for knowledge exchange”. british. In: *The Journal of Technology Transfer* 45.1 (2018), pp. 1–8. DOI: `10.1007/s10961-018-9677-1`.

[53] Alpaydin, U. A. R. *University-Industry Collaborations (UICs): A Matter of Proximity Dimensions?* british. PhD Thesis. 2021. URL: `https://hdl.handle.net/11250/2732397`.

[54] Sigrid Rajalo and Maaja Vadi. “University-industry innovation collaboration: Reconceptualization”. british. In: *Technovation* 62 (2017), pp. 42–54. DOI: `10.1016/j.technovation.2017.04.003`.

[55] Olga Petricevic and Alain Verbeke. “Unbundling dynamic capabilities for inter-organizational collaboration”. british. In: *Cross Cultural Strategic Management* 26.3 (2019), pp. 422–448. DOI: `10.1108/ccsm-02-2019-0044`.

[56] Paul Jackson et al. “University–industry collaboration within the triple helix of innovation: The importance of mutuality”. british. In: *Science and Public Policy* 45.4 (2017), pp. 553–564. DOI: `10.1093/scipol/scx083`.

[57] Karolin Sjöö and Tomas Hellström. “University–industry collaboration: A literature review and synthesis”. british. In: *Industry and Higher Education* 33.4 (2019), pp. 275–285. DOI: `10.1177/0950422219829697`.

[58] Vivianna Fang He et al. “Asymmetries between partners and the success of university-industry research collaborations”. british. In: *Research Policy* 50.10 (2021), p. 104356. DOI: `10.1016/j.respol.2021.104356`.

[59] Markus Perkmann and Kathryn Walsh. “University–industry relationships and open innovation: Towards a research agenda”. british. In: *International Journal of Management Reviews* 9.4 (2007), pp. 259–280. DOI: `10.1111/j.1468-2370.2007.00225.x`.

[60] Markus Perkmann et al. “Academic Engagement: A Review of the Literature 2011-2019”. british. In: *SSRN Electronic Journal* (2019). DOI: `10.2139/ssrn.3461621`.

[61] Rudi Bekkers and Isabel Maria Bodas Freitas. “Analysing knowledge transfer channels between universities and industry: To what degree do sectors also matter?” british. In: *Research Policy* 37.10 (2008), pp. 1837–1853. DOI: `10.1016/j.respol.2008.07.007`.

[62] Claudia De Fuentes and Gabriela Dutrénit. “Best channels of academia–industry interaction for long-term benefit”. british. In: *Research Policy* 41.9 (2012), pp. 1666–1682. DOI: `10.1016/j.respol.2012.03.026`.

[63] Jiancheng Guan and Qingjun Zhao. “The impact of university–industry collaboration networks on innovation in nanobiopharmaceuticals”. british. In: *Technological Forecasting and Social Change* 80.7 (2013), pp. 1271–1286. DOI: `10.1016/j.techfore.2012.11.013`.

[64] Yong S. Lee. “‘Technology transfer’ and the research university: a search for the boundaries of university-industry collaboration”. british. In: *Research Policy* 25.6 (1996), pp. 843–863. DOI: `10.1016/0048-7333(95)00857-8`.

[65] Donald S Siegel et al. “Commercial knowledge transfers from universities to firms: improving the effectiveness of university–industry collaboration”. british. In: *The Journal of High Technology Management Research* 14.1 (2003), pp. 111–133. DOI: `10.1016/s1047-8310(03)00007-5`.

[66] Johan Bruneel, Pablo D’Este, and Ammon Salter. “Investigating the factors that diminish the barriers to university–industry collaboration”. british. In: *Research Policy* 39.7 (2010), pp. 858–868. DOI: `10.1016/j.respol.2010.03.006`.

[67] Josef Gochermann and Sandra Bense. “Enhancement of Knowledge through Circulation in Networks of RD Institutions and Companies”. british. In: *Industry and Higher Education* 18.5 (2004), pp. 299–307. DOI: `10.5367/0000000042317355`.

[68] Christian Nielsen and Katja Cappelen. “Exploring the Mechanisms of Knowledge Transfer in University-Industry Collaborations: A Study of Companies, Students and Researchers”. british. In: *Higher Education Quarterly* 68.4 (2014), pp. 375–393. DOI: `10.1111/hequ.12035`.

[69] Michaal Bikard, Keyvan Vakili, and Florenta Teodoridis. “When Collaboration Bridges Institutions: The Impact of Industry Collaboration on Academic Productivity”. british. In: *SSRN Electronic Journal* (2016). DOI: `10.2139/ssrn.2883365`.

[70] Markus Perkmann et al. “Academic engagement and commercialisation: A review of the literature on university–industry relations”. british. In: *Research Policy* 42.2 (2013), pp. 423–442. DOI: `10.1016/j.respol.2012.09.007`.

[71] Mervi Huhtelin and Suvi Nenonen. “A Co-creation Centre for University–Industry Collaboration – A Framework for Concept Development”. british. In: *Procedia Economics and Finance* 21 (2015), pp. 137–145. DOI: `10.1016/s2212-5671(15)00160-4`.

[72] Sreejith Balasubramanian et al. “A readiness assessment framework for Blockchain adoption: A healthcare case study”. british. In: *Technological Forecasting and Social Change* 165 (2021), p. 120536. DOI: `10.1016/j.techfore.2020.120536`.

[73] David Romero, Nathalie Galeano, and Arturo Molina. "Mechanisms for assessing and enhancing organisations' readiness for collaboration in collaborative networks". british. In: *International Journal of Production Research* 47.17 (2009), pp. 4691–4710. DOI: `10.1080/00207540902847280`.

[74] Fred D. Davis. "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology". british. In: *MIS Quarterly* 13.3 (1989), p. 319. DOI: `10.2307/249008`.

[75] Chien-Hsin Lin, Hsin-Yu Shih, and Peter J. Sher. "Integrating technology readiness into technology acceptance: The TRAM model". british. In: *Psychology and Marketing* 24.7 (2007), pp. 641–657. DOI: `10.1002/mar.20177`.

[76] A. Parasuraman. "Technology Readiness Index (Tri)". british. In: *Journal of Service Research* 2.4 (2000), pp. 307–320. DOI: `10.1177/109467050024001`.

[77] Gaetano R. Lotrecchiano et al. "Individual motivation and threat indicators of collaboration readiness in scientific knowledge producing teams: a scoping review and domain analysis". british. In: *Heliyon* 2.5 (2016), e00105. DOI: `10.1016/j.heliyon.2016.e00105`.

[78] Kirsimarja Blomqvist, Pia Hurmelinna, and Risto Seppänen. "Playing the collaboration game right—balancing trust and contracting". british. In: *Technovation* 25.5 (2005), pp. 497–504. DOI: `10.1016/j.technovation.2004.09.001`.

[79] Christopher Durugbo. "Collaborative networks: a systematic review and multi-level framework". british. In: *International Journal of Production Research* 54.12 (2015), pp. 3749–3776. DOI: `10.1080/00207543.2015.1122249`.

[80] David Romero, Nathalie Galeano, and Arturo Molina. "Readiness for Collaboration Assessment Approach in Collaborative Networked Organisations". british. In: *Innovation in Manufacturing Networks* (2008), pp. 47–56. DOI: `10.1007/978-0-387-09492-2_5`.

[81] João Rosas and Luis M. Camarinha-Matos. "An approach to assess collaboration readiness". british. In: *International Journal of Production Research* 47.17 (2009), pp. 4711–4735. DOI: `10.1080/00207540902847298`.

[82] Andrew Forbes, Francesco Petruccione, and Filippus S. Roux. "Toward a quantum future for South Africa". british. In: *AVS Quantum Science* 3.4 (2021), p. 040501. DOI: `10.1116/5.0060426`.

[83] Kim et al. "The Future of Quantum Information: Challenges and Vision". british. In: *Journal of Information Processing Systems* 17.1 (2021), pp. 151–162. DOI: `10.3745/JIPS.01.0063`.

[84] Chicago Quantum. *CHICAGO QUANTUM EXCHANGE*. british. 2020. URL: `https://chicagoquantum.org/sites/default/files/2021-07/AnnualReport2020.pdf`.

[85] Peterssen. *Quantum technology impact: the necessary workforce for developing quantum software*. british. 2020.

[86] Srivastava, Choi, and Cook. *The Commercial Prospects for Quantum Computing*. british. Issue 1. Dec. 2016. URL: `https://qutip.org/news/Commercial_Prospects_for_Quantum_Computing_Dec_2016.pdf`.

[87] Inglesant, Hartswood, and Jirotka. *Thinking Ahead to a World with Quantum Computers The Landscape of Responsible Research and Innovation in Quantum Computing*. british. 2016. URL: `https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2016-11/RRI%20Landscape%20Report%20November%202016.pdf`.

[88] *Quantum engineering course in the making*. Dutch. June 21, 2021. URL: `https://www.delta.tudelft.nl/article/quantum-engineering-course-making` (visited on 03/14/2022).

[89] Rathenau Instituut. *Onderzoeksinzet universiteiten*. Dutch. Aug. 31, 2021. URL: `https://www.rathenau.nl/nl/wetenschap-cijfers/wetenschappers/personeel-aan-de-universiteiten-en-umcs/onderzoeksinzet` (visited on 03/14/2022).

[90] NWO. *NWO | Wat NWO doet*. Dutch. 2019. URL: `https://www.nwo.nl/wat-nwo-doet` (visited on 03/14/2022).

[91] Quantum Flagship. *Introduction to the Quantum Flagship*. Sept. 3, 2020. URL: `https://qt.eu/about-quantum-flagship/introduction-to-the-quantum-flagship/` (visited on 03/14/2022).

[92] Universiteiten van Nederland. *Bekostiging universiteiten.* Dutch. 2010. URL: `https://www.universiteitenvannederland.nl/bekostiging-universiteiten.html` (visited on 03/14/2022).

[93] NWO. *NWO | NWO-strategie 2019-2022.* Dutch. 2019. URL: `https://www.nwo.nl/nwo-strategie-2019-2022` (visited on 03/14/2022).

[94] European Commission. *Before you apply: EU funding for beginners.* 2020. URL: `https://ec.europa.eu/info/funding-tenders/how-apply/you-apply-eu-funding-beginners_en#:$%5C%$7E:text=There$%5C%$20are$%5C%$20different$%5C%$20types$%5C%$20of,governed$%5C%$20by$%5C%$20the$%5C%$20Financial$%5C%$20Regulation.` (visited on 03/14/2022).

[95] Nature Editorial. *Europe shows first cards in €1-billion quantum bet.* Oct. 29, 2018. URL: `https://www.nature.com/articles/d41586-018-07216-0?error=cookies_not_supported&code=6249e189-67e1-44ff-ab67-b7d35d59d363` (visited on 04/06/2022).

[96] NIST. *The Second Quantum Revolution.* Mar. 30, 2018. URL: `https://www.nist.gov/topics/physics/introduction-new-quantum-revolution/second-quantum-revolution` (visited on 03/14/2022).

[97] European Commission. *Quantum Technologies Flagship.* Dec. 16, 2021. URL: `https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship#:$%5C%$7E:text=The$%5C%$20Quantum$%5C%$20Technologies$%5C%$20Flagship$%5C%$20is,1$%5C%$20billion$%5C%$20from$%5C%$20the$%5C%$20EU` (visited on 03/14/2022).

[98] Bright. *Google claimt doorbraak quantumcomputer, IBM bestrijdt die claim.* Dutch. Oct. 24, 2019. URL: `https://www.rtlnieuws.nl/tech/artikel/4895646/google-quantumcomputer-intel-quantumsuperioriteit` (visited on 03/14/2022).

[99] Frank Arute. *Quantum computing takes flight.* Oct. 23, 2019. URL: `https://www.nature.com/articles/s41586-019-1666-5?error=cookies_not_supported&code=58b6ff74-5abc-4408-a8c3-0833d28e83da` (visited on 03/14/2022).

[100] IBM. *The qubit.* 2022. URL: `https://quantum-computing.ibm.com/composer/docs/iqx/guide/the-qubit` (visited on 03/14/2022).

[101] Microsoft Quantum Team. *Developing a topological qubit.* Feb. 14, 2020. URL: `https://cloudblogs.microsoft.com/quantum/2018/09/06/developing-a-topological-qubit/` (visited on 03/14/2022).

[102] Caudillo. *Intel Superconducting Qubits, Part 1: Performance improvements towards enabling quantum applications.* 2019. URL: `https://ui.adsabs.harvard.edu/abs/2019APS..MARS35011C/abstract` (visited on 03/14/2022).

[103] Intel. *Intel and QuTech Demonstrate High-Fidelity 'Hot' Qubits for Practical Quantum Systems.* May 29, 2020. URL: `https://newsroom.intel.com/news/intel-qutech-demonstrate-high-fidelity-hot-qubits-practical-quantum-systems/#gs.seyzwy` (visited on 03/14/2022).

[104] Olaf van Miltenburg. *De race naar een quantumcomputer - Wint Google, IBM of Microsoft?* Dutch. Jan. 28, 2018. URL: `https://tweakers.net/reviews/5981/2/de-race-naar-een-quantumcomputer-wint-google-ibm-of-microsoft-google-op-zoek-naar-quantum-supremacy.html` (visited on 03/14/2022).

[105] Heera Dijk. *Quantum institute enters into collaboration with Intel.* Sept. 3, 2015. URL: `https://qutech.nl/2015/09/03/qutechentersintocollaborationwithintel/` (visited on 04/12/2022).

[106] Webredactie communication. *Nieuw systeem binnen toekomstig quantum internet maakt onaftapbare communicatie mogelijk.* Dutch. July 6, 2021. URL: `https://www.tudelft.nl/2021/tu-delft/nieuw-systeem-binnen-toekomstig-quantum-internet-maakt-onaftapbare-communicatie-mogelijk` (visited on 03/14/2022).

[107] Rianne Flikweert. *Quantum technology for secure banking: teams up with ABN AMRO.* May 15, 2020. URL: `https://qutech.nl/2019/06/26/quantum-technology-for-secure-banking-qutech-teams-up-with-abn-amro/` (visited on 03/14/2022).

[108] Rianne Flikweert. *KPN and join forces to make quantum internet a reality.* June 19, 2019. URL: `https://qutech.nl/2019/06/19/kpn-and-qutech-join-forces-to-make-quantum-internet-a-reality/` (visited on 04/12/2022).

[109] Capgemini. *Quantum Technologies and Capgemini's Q Lab*. Mar. 31, 2022. URL: https://www.capgemini.com/our-company/technology-innovation-ventures/quantum-technologies-and-capgeminis-q-lab/ (visited on 04/06/2022).

[110] Bosch Global. *Quantum technology is opening up new dimensions*. 2022. URL: https://www.bosch.com/stories/quantum-technology/ (visited on 04/12/2022).

[111] Bak. *TNO spin-off levert gereedschap voor onderzoek naar quantumtechnologie*. Dutch. Nov. 16, 2021. URL: https://www.4tu.nl/nieuws/spinoff-verhaal-TNO-quantum/ (visited on 03/14/2022).

[112] European Commission. *SME definition*. 2003. URL: https://ec.europa.eu/growth/smes/sme-definition_en (visited on 03/14/2022).

[113] Bluefors. *Bluefors dilution refrigerator systems for quantum technology and research*. 2019. URL: https://bluefors.com/ (visited on 04/12/2022).

[114] The Quantum Vision Team. *Quantum Internet, The internet's next big step*. british. June 2019. URL: https://d2k0ddhflgrk1i.cloudfront.net/Websections/Vision$%5C%$20teams/Quantum$%5C%$20computing/quantum$%5C%$20magazine$%5C%$20june$%5C%$202019.pdf.

[115] Silvan Schoonhoven. *AIVD waarschuwt voor kwantumcomputer: geen geheim meer veilig*. Dutch. Jan. 19, 2022. URL: https://www.telegraaf.nl/nieuws/694875866/aivd-waarschuwt-voor-kwantumcomputer-geen-geheim-meer-veilig (visited on 04/06/2022).

[116] Nato van Amerongen. *Quantum technologies in defence security*. british. June 3, 2021. URL: https://www.nato.int/docu/review/articles/2021/06/03/quantum-technologies-in-defence-security/index.html (visited on 04/12/2022).

[117] S N. Ankrah and Omar Al-Tabbaa. "Universities-Industry Collaboration: A Systematic Review". british. In: *SSRN Electronic Journal* 31.3 (2015). DOI: 10.2139/ssrn.2596018.

[118] Roulla Hagen. "Globalization, university transformation and economic regeneration". british. In: *International Journal of Public Sector Management* 15.3 (2002), pp. 204–218. DOI: 10.1108/09513550210423370.

[119] Christine Oliver. "Determinants of Interorganizational Relationships: Integration and Future Directions". british. In: *Academy of Management Review* 15.2 (1990), pp. 241–265. DOI: 10.5465/amr.1990.4308156.

[120] *Personal Motivations | Collaboration Canvas*. 2022. URL: http://collaborationcanvas.changingworld.eu/index.php/personal-motivations/ (visited on 05/04/2022).

[121] Markus Perkmann, Zella King, and Stephen Pavelin. "Engaging excellence? Effects of faculty quality on university engagement with industry". british. In: *Research Policy* 40.4 (2011), pp. 539–552. DOI: 10.1016/j.respol.2011.01.007.

[122] Grant Harman and Val Sherwell. "Risks in University-Industry Research Links and the Implications for University Management". british. In: *Journal of Higher Education Policy and Management* 24.1 (2002), pp. 37–51. DOI: 10.1080/13600800220130752.

[123] David Blumenthal. "Academic–Industrial Relationships in the Life Sciences". british. In: *New England Journal of Medicine* 349.25 (2003), pp. 2452–2459. DOI: 10.1056/nejmhpr035460.

[124] J. Lee and H.N. Win. "Technology transfer between university research centers and industry in Singapore". british. In: *Technovation* 24.5 (2004), pp. 433–442. DOI: 10.1016/s0166-4972(02)00101-3.

[125] Dixon. "The "Market Pull" versus "Technology Push" Continuum of Engineering Education". british. In: American Society for Engineering Education Annual Conference Exposition. American Society for Engineering Education, 2001.

[126] Tina Barnes, Ian Pashby, and Anne Gibbons. "Effective University – Industry Interaction:" british. In: *European Management Journal* 20.3 (2002), pp. 272–285. DOI: 10.1016/s0263-2373(02)00044-0.

[127] Donald S Siegel et al. "Toward a model of the effective transfer of scientific knowledge from academicians to practitioners: qualitative evidence from the commercialization of university technologies". british. In: *Journal of Engineering and Technology Management* 21.1-2 (2004), pp. 115–142. DOI: `10.1016/j.jengtecman.2003.12.006`.

[128] Robert M. Grant. "Prospering in Dynamically-Competitive Environments: Organizational Capability as Knowledge Integration". british. In: *Organization Science* 7.4 (1996), pp. 375–387. DOI: `10.1287/orsc.7.4.375`.

[129] Donald S Siegel, David Waldman, and Albert Link. "Assessing the impact of organizational practices on the relative productivity of university technology transfer offices: an exploratory study". british. In: *Research Policy* 32.1 (2003), pp. 27–48. DOI: `10.1016/s0048-7333(01)00196-2`.

[130] S.N. Ankrah et al. "Asking both university and industry actors about their engagement in knowledge transfer: What single-group studies of motives omit". british. In: *Technovation* 33.2-3 (2013), pp. 50–65. DOI: `10.1016/j.technovation.2012.11.001`.

[131] Keith Pavitt. "The social shaping of the national science base". british. In: *Research Policy* 27.8 (1998), pp. 793–805. DOI: `10.1016/s0048-7333(98)00091-2`.

[132] Doris Schartinger et al. "Knowledge interactions between universities and industry in Austria: sectoral patterns and determinants". british. In: *Research Policy* 31.3 (2002), pp. 303–328. DOI: `10.1016/s0048-7333(01)00111-1`.

[133] Gerard George, Shaker A Zahra, and D.Robley Wood. "The effects of business–university alliances on innovative output and financial performance: a study of publicly traded biotechnology companies". british. In: *Journal of Business Venturing* 17.6 (2002), pp. 577–609. DOI: `10.1016/s0883-9026(01)00069-6`.

[134] James Price Dillard. "Goals–Plan–Action Theory". british. In: *The International Encyclopedia of Interpersonal Communication* (2015), pp. 1–5. DOI: `10.1002/9781118540190.wbeic148`.

[135] James Price Dillard. *Seeking compliance: The production of interpersonal influence messages.* Gorsuch Scarisbrick, 1990.

[136] Quantum Delft. *Be part of the quantum revolution.* british. Apr. 25, 2022. URL: `https://quantumdelft.nl/` (visited on 05/05/2022).

[137] Reinhilde Veugelers and Bruno Cassiman. "R&D cooperation between firms and universities. Some empirical evidence from Belgian manufacturing". In: *International Journal of Industrial Organization* 23.5-6 (2005), pp. 355–379.

[138] Jasmina Berbegal-Mirabent, Esteban Lafuente, and Francesc Solé. "The pursuit of knowledge transfer activities: An efficiency analysis of Spanish universities". In: *Journal of Business Research* 66.10 (2013), pp. 2051–2059.

[139] Rudi Bekkers and I Bodas-Freitas. "Catalysts and barriers: Factors that affect the performance of university-industry collaborations". In: *Conference paper international schumpeter society conference.* 2010, pp. 1–24.

[140] Wesley M Cohen, Richard R Nelson, and John P Walsh. "Links and impacts: the influence of public research on industrial R&D". In: *Management science* 48.1 (2002), pp. 1–23.

[141] Roberto Fontana, Aldo Geuna, and Mireille Matt. "Factors affecting university–industry R&D projects: The importance of searching, screening and signalling". In: *Research policy* 35.2 (2006), pp. 309–323.

[142] Sanjay Jain, Gerard George, and Mark Maltarich. "Academics or entrepreneurs? Investigating role identity modification of university scientists involved in commercialization activity". In: *Research policy* 38.6 (2009), pp. 922–935.

[143] Eduardo Rodrigues. *Creating a startup ecosystem: 6 pillars of success.* Aug. 13, 2018. URL: `https://www.linkedin.com/pulse/20140728145028-95191794-creating-a-startup-ecosystem-6-pillars-of-success/` (visited on 04/11/2022).

[144] Knockaert et al. "The Relationship Between Knowledge Transfer, Top Management Team Composition, and Performance: The Case of Science-Based Entrepreneurial Firms". british. In: *Entrepreneurship Theory and Practice* 35.4 (2011), pp. 777–803. DOI: `10.1111/j.1540-6520.2010.00405.x`.

[145] David Blumenthal et al. "Participation of Life-Science Faculty in Research Relationships with Industry". british. In: *New England Journal of Medicine* 335.23 (1996), pp. 1734–1739. DOI: `10.1056/nejm199612053352305`.

[146] Eric G Campbell et al. "Data withholding in academic medicine: characteristics of faculty denied access to research results and biomaterials". british. In: *Research Policy* 29.2 (2000), pp. 303–312. DOI: `10.1016/s0048-7333(99)00068-2`.

[147] *Cancelled project spurs debate over geoengineering patents.* May 24, 2012. URL: `https://www.nature.com/articles/485429a?error=cookies_not_supported&code=c208a895-7658-4fc1-95e9-a99b469cfbed` (visited on 04/06/2022).

[148] Robert J. Lavidge and Gary A. Steiner. "A Model for Predictive Measurements of Advertising Effectiveness". british. In: *Journal of Marketing* 25.6 (1961), p. 59. DOI: `10.2307/1248516`.

[149] Scott Edward Rutledge and Neil Abell. "Awareness, Acceptance, and Action: An Emerging Framework for Understanding AIDS Stigmatizing Attitudes among Community Leaders in Barbados". british. In: *AIDS Patient Care and STDs* 19.3 (2005), pp. 186–199. DOI: `10.1089/apc.2005.19.186`.

[150] N. Abell and S. E. Rutledge. "Awareness, Acceptance and Action: Developing Mindful Collaborations in International HIV/AIDS Research and Service". british. In: *British Journal of Social Work* 40.2 (2009), pp. 656–675. DOI: `10.1093/bjsw/bcp047`.

[151] Quantum for Business. *About / Quantum For Business.* british. 2022. URL: `https://www.quantumforbusiness.eu/about-quantum-for-business` (visited on 04/12/2022).

[152] Daniel Stokols et al. "The Ecology of Team Science". british. In: *American Journal of Preventive Medicine* 35.2 (2008), S96–S115. DOI: `10.1016/j.amepre.2008.05.003`.

[153] Delft University of Technology. *Netherlands Code of Conduct for Research Integrity.* Oct. 1, 2018. URL: `https://www.tudelft.nl/en/about-tu-delft/strategy/integrity-policy/academic-integrity/netherlands-code-of-conduct-for-research-integrity` (visited on 04/22/2022).

[154] Samuel Gregory Blane Johnson, Avri Bilovich, and David Tuckett. "Conviction Narrative Theory: A Theory of Choice Under Radical Uncertainty". british. In: *Preprint* (2020). DOI: `10.31234/osf.io/urc96`.

Appendix A

Results without corrections

In the main text, only the results which are corrected for known measurement errors and with events where at least one of the two devices was in the incorrect charge state removed are presented. Although it is beneficial to correct for such errors in order to obtain the most accurate reconstruction of the delivered states, such errors cannot always be avoided in a real network environment. So to be complete, in this appendix the results with and without any corrections applied are reported. In addition to this, the results with only the measurement error correction applied are stated.

A.1 Full state quantum tomography of the delivered states.

The exact values and uncertainties of the reconstructed density matrix with both measurement and incorrect charge state corrections, and overall fidelity of $F = 0.783(7)$, are:

$$\mathrm{Re}[\rho] = \begin{pmatrix} 0.442(6) & 0.003(3) & 0.003(2) & 0.328(5) \\ 0.003(3) & 0.033(6) & -0.023(5) & -0.000(5) \\ 0.003(2) & -0.023(5) & 0.056(4) & -0.003(4) \\ 0.328(5) & -0.000(5) & -0.003(4) & 0.469(7) \end{pmatrix}$$

$$\mathrm{Im}[\rho] = \begin{pmatrix} 0 & -0.014(3) & -0.005(7) & 0.032(5) \\ 0.014(3) & 0 & -0.002(4) & 0.001(5) \\ 0.005(7) & 0.002(4) & 0 & -0.000(7) \\ -0.032(5) & -0.001(5) & 0.000(7) & 0 \end{pmatrix}$$

In the CR-check after the measurement, the two devices generated 0 photon counts 37 times for the client and 380 times for the server (out of the 4500 total). When added together, client or server in the incorrect charge state), 417 events are obtained (in zero events both client and server were in the wrong charge state). We get the following density matrix (which has a fidelity with the target Bell state $F = 0.681(16)$) without any corrections (tomography mistakes or incorrect charge state):

$$\mathrm{Re}[\rho] = \begin{pmatrix} 0.397(9) & 0.011(9) & 0.001(7) & 0.256(14) \\ 0.011(9) & 0.058(14) & -0.005(13) & -0.007(9) \\ 0.001(7) & -0.005(13) & 0.092(12) & -0.027(13) \\ 0.256(14) & -0.007(9) & -0.027(13) & 0.452(9) \end{pmatrix}$$

$$\mathrm{Im}[\rho] = \begin{pmatrix} 0 & 0.000(18) & -0.029(9) & 0.036(9) \\ -0.000(18) & 0 & 0.010(12) & -0.002(8) \\ 0.029(9) & -0.010(12) & 0 & -0.000(8) \\ -0.036(9) & 0.002(8) & 0.000(8) & 0 \end{pmatrix}$$

The density matrix (fidelity $F = 0.744(11)$) is obtained by only performing tomography error correction (but not by removing incorrect charge state events):

$$\mathrm{Re}[\rho] = \begin{pmatrix} 0.421(7) & -0.001(4) & -0.013(5) & 0.300(8) \\ -0.001(4) & 0.022(8) & -0.020(6) & -0.021(7) \\ -0.013(5) & -0.20(6) & 0.091(5) & -0.015(5) \\ 0.300(8) & -0.021(7) & -0.015(5) & 0.466(5) \end{pmatrix}$$

$$\mathrm{Im}[\rho] = \begin{pmatrix} 0 & 0.004(4) & -0.018(3) & 0.032(6) \\ -0.004(4) & 0 & 0.021(6) & 0.002(5) \\ 0.018(3) & -0.021(6) & 0 & 0.002(5) \\ -0.032(6) & -0.002(5) & -0.002(5) & 0 \end{pmatrix}$$

A.2 Requested fidelity versus latency

In the CR-check after the measurement, the two devices generated 0 photon counts 74 times for the client and 709 times for the server (out of the 10500 total). When added together, client or server in the incorrect charge state), 781 events are obtained (in two events both client and server were in the wrong charge state). We obtained the following delivered fidelities for the seven requested fidelities (0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80):

- With both tomography and incorrect charge state corrections:
  0.500(16), 0.612(14), 0.608(15), 0.686(13), 0.742(12), 0.784(11), 0.796(11).
- Without any corrections (tomography errors or incorrect charge state corrections):
  0.454(18), 0.540(18), 0.548(17), 0.596(17), 0.640(16), 0.674(16), 0.679(15).
- Only applying tomography error correction (but not removal of incorrect charge state events):
  0.485(15), 0.591(14), 0.592(14), 0.652(13), 0.705(13), 0.741(12), 0.753(11).

A.3 Remote state preparation of a qubit

Following are the numerical values also printed in the main text (average fidelity $F = 0.853(8)$):

Table A.1: ***Remote state preparation tomography with tomography and incorrect charge state corrections.*** *The 4500 entangled states of the remote state preparation measurement are grouped by the states prepared on the qubit of the server, resulting in 6 data sets (prepared states by the client:* $|+X\rangle, |-X\rangle, |+Y\rangle, |-Y\rangle, |+Z\rangle, |-Z\rangle$*). For each data set, the expectation values for each server measurement basis are estimated. These values are corrected for the known server tomography error and removal of events in which either device was in then incorrect charge state. In the outer right column, the fidelity of the targeted prepared state is determined. The uncertainties of the expectation values and fidelities are displayed between parenthesis.*

Client	Server			
	$\langle X\rangle$	$\langle Y\rangle$	$\langle Z\rangle$	Fidelity
Measured $|+X\rangle$	0.634(48)	-0.123(62)	-0.004(59)	0.817(24)
Measured $|-X\rangle$	-0.645(43)	0.135(59)	0.030(63)	0.823(22)
Measured $|+Y\rangle$	-0.028(58)	-0.650(45)	0.005(61)	0.825(23)
Measured $|-Y\rangle$	0.026(65)	0.719(40)	-0.013(61)	0.860(20)
Measured $|+Z\rangle$	-0.081(65)	-0.083(66)	0.849(31)	0.924(16)
Measured $|-Z\rangle$	0.032(58)	-0.069(58)	-0.736(39)	0.868(19)

In the CR-check after the measurement, the two devices generated 0 photon counts 29 times for the client and 365 times for the server (out of the 4500 total). When added together, client or server in the incorrect charge state), 394 events are obtained (in zero events both client and server were in the wrong charge state). The following prepared states are obtained without any corrections (tomography errors or incorrect charge state corrections) with average fidelity $F = 0.807(10)$:

Table A.2: ***Remote state preparation tomography without any corrections.***

Client	Server			
	$\langle X\rangle$	$\langle Y\rangle$	$\langle Z\rangle$	Fidelity
Measured $\|{+X}\rangle$	0.534(55)	-0.090(62)	0.009(62)	0.767(27)
Measured $\|{-X}\rangle$	-0.552(49)	0.143(61)	0.055(63)	0.776(24)
Measured $\|{+Y}\rangle$	0.024(60)	-0.582(51)	-0.013(62)	0.791(26)
Measured $\|{-Y}\rangle$	0.052(64)	0.623(47)	-0.018(62)	0.811(23)
Measured $\|{+Z}\rangle$	-0.073(69)	-0.072(69)	0.786(42)	0.893(21)
Measured $\|{-Z}\rangle$	0.030(57)	-0.028(55)	-0.606(46)	0.803(23)

The following prepared states are obtained with only applying tomography error correction (but not removal of incorrect charge state events) with average fidelity $F = 0.829(9)$:

Table A.3: ***Remote state preparation tomography with only applying tomography error correction.***

Client	Server			
	$\langle X\rangle$	$\langle Y\rangle$	$\langle Z\rangle$	Fidelity
Measured $\|{+X}\rangle$	0.573(49)	-0.096(59)	0.010(58)	0.786(24)
Measured $\|{-X}\rangle$	-0.592(44)	0.153(57)	0.059(59)	0.796(22)
Measured $\|{+Y}\rangle$	0.025(56)	-0.624(45)	-0.014(59)	0.812(23)
Measured $\|{-Y}\rangle$	0.056(61)	0.667(41)	-0.020(59)	0.834(20)
Measured $\|{+Z}\rangle$	-0.078(64)	-0.077(65)	0.843(32)	0.921(16)
Measured $\|{-Z}\rangle$	0.032(54)	-0.030(53)	-0.650(40)	0.825(20)