Schrödinger’s Cat wants to Play.

A Game Theory Inspired Approach to the Assessment of Quantum Network Technologies.

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Master Thesis

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For those close to me I'd like to continue in Dutch

Ik wil mijn ouders bedanken. Filosofie en natuurkunde zullen voor jullie beide waarschijnlijk vreemde wereld blijven, maar dat is niet erg. Dank dat ik bij jullie een plekje in Nijkerk had waar ik juist even niet bezig hoefde te zijn met de grote vragen van het universum.

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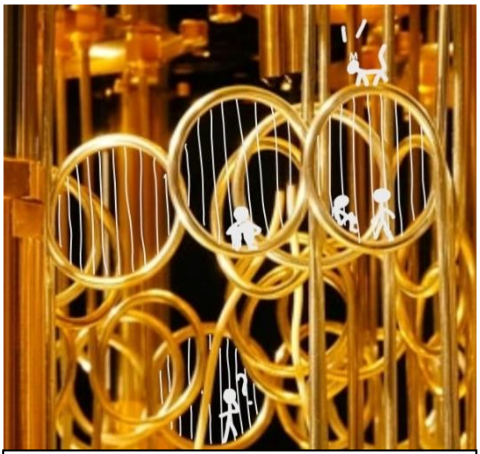

Spelen in de quantum gevangenis
(Translated: Playing in the Quantum Prison)
Drawn by: Koosje van der Lecq

Ja man. Al het mooie komt tot een eind. Dit is het bewijs. – Joost (2022)

Abstract

This thesis explores quantum network technologies through the mathematical field of game theory. Quantum network technologies bring possibilities for connecting computational devices in a novel way. Through a game theory-inspired methodology, this thesis explores how interactions between users in a quantum network can develop. The main research question is: How can the development and governance of quantum networks be guided by the field of game theory? Two recommendations on the governance of a quantum network are developed by building a normative game theory model that incorporates the novel capabilities of a quantum network. The first recommendation on redundancy shows that the governance of a quantum network will benefit from more participants. The second recommendation shows the benefit of a retaliating but forgiving strategy in punishing misbehavior. Overall, the use of game theory in the assessment of quantum technologies brings interesting lessons. The end of the thesis reflects on the future use of game theory to assess technologies such as quantum networks, which shows potential, but should be done with care.

Contents

Introduction

In 1959, Physicist Richard Feynman gave a talk at the California Institute of Technology where he proclaimed that "There's Plenty of Room at the Bottom" (Feynman, 1960). With this statement, Feynman heralds the science of manipulating and storing information at the tiniest scale. In 2017, Physicist David P. DiVincenzo responded to Feynman's claim 60-year-old claim that "There is now no more room at the bottom" (DiVincenzo, 2017, p. 247). Feynman and DiVincenzo respectively proclaimed and established the arrival of a particular research field that deals with engineering at the smallest scale known to physics: quantum technology.

The arrival of quantum technology (QT) comes with interesting consequences. QT has specific capabilities that are not to be found in any other technology. Some of the fields that QT will disrupt are internet security (cryptography), algorithm development, and simulating quantum systems (De Wolf, 2017). The nuances of QT, and predicting its' disruption is not a trivial endeavor. This is because QT is not one singular technology, but instead a family of technologies related through their affiliation with quantum physics and how they exploit quantum phenomena.

One subset of QT is quantum networking (QN). QN allows for novel ways of information exchange between actors. The fact that QN connects different users, gives rise to specific questions. Technologies that allow for connectivity cannot be studied in isolation, nor just through a human-technology relation framework. If a technology connects multiple users, there is a need to study the user-user interactions that the technology facilitates. If QN are to be regulated responsibly, we should consider the dynamics that are at play between actors.

This thesis aims to explore a new way of studying QN technologies, namely through the mathematical field of game theory (GT). GT is a field of modeling concerned with the study of interaction choice. GT studies how systems of independent decision-makers evolve.

The aim of combining these two, seemingly unrelated fields, is to approach the assessment of QT in a novel fashion. New technologies require new approaches, and QT is deemed worthy of such attention (De Jong, 2022; De Wolf, 2017; Gasser et al., 2024). Therefore, attempting uncommon methods can be quite valuable. The specific research question of this thesis is: **How can the development and management of quantum networks be guided by the field of game theory?** This main question is answered through three chapters. The first and second chapters are concerned with setting the stage for the first (QN) and second half (GT) of the main question respectively. The third chapter is the culmination of the two. A more elaborate description of the sub-chapter structure is in the chapter division below.

There are preliminary signs that hint at combining QN with GT as a valuable endeavor. One sign is a forthcoming paper by Possati & Vermaas (Forthcoming). Their paper takes an analytic approach to connecting quantum computers.[1] Their work does not explicitly name GT as a methodology but there are signs of similarity between this paper and theirs.[2] The similarities and differences are discussed at multiple points throughout this thesis.

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[1] As will become clear throughout the thesis, connecting quantum computers will be a central aspect of analysis in the GT-approach too.

[2] These similarities are not just in the writing, but also emerged through discussion with the author Luca Possati about the paper in context of this thesis.

Another sign of success is that both QN and GT are about connectivity and interaction. QN systems facilitate computational interactions between people through a physical network of wires, signals, and GT studies interactions. Of course, both fields are far more complex than these simple descriptions. This thesis is the playground to test whether the synergy holds if we go beyond these superficial similarities.

Chapter Division and Sub-Questions

The main research question is answered throughout three chapters. Chapters 1 and 2 focus on QT and GT respectively. Chapter 3 details the results and specific lessons that emerged from their fusion. The contents of the chapter are as follows.

Chapter 1 concerns ***the development and management of quantum networks***. The chapter details what quantum network technology is, what it can do, what is needed in its construction, and who will use it. The aim is to start with a theoretical and technical understanding of QT and work towards a specific QN case that can be used throughout the remainder of the thesis. The section division is as follows:

(1) Understanding quantum
    a. Because quantum is often considered a notoriously complex field, this chapter starts with a reflection on what it means to understand quantum. This sets the scope for the technical analysis.
(2) Introduce the technology
    a. The field of QT is described with a particular focus on QN, as QN is the focus of the thesis.
(3) Quantum networks
    a. Zoom in on quantum networks specifically.
    b. Because computational networks are technologies of connectivity, specific attention is spent on what can be done with these connections and who will be using them. This scenario details the relevant actors and their possibility for decision-making in the context of this system.
(4) The quantum case
    a. The final section of Chapter 1 reorganizes all the information into a case which can be used for analysis throughout the remainder of the Thesis.

Chapter 2 concerns what it means to **be guided by the field of game theory.** GT as a mathematical field has no immediate applicability to explore QN dynamics. Therefore, a specific methodology must be established. This chapter starts by describing the field of GT and built towards a specific GT-inspired[3] methodology to study the case from the previous chapter. The section division is as follows:

(1) Brief introduction to game theory
    a. The chapter starts with a general description of the history and content of GT.
(2) The different uses of game theory
    b. The chapter zooms in on a particular set of GT terminology and examples. These terminologies and examples help in grasping the field of GT and serve as the groundwork for the methodology.

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[3] The decision to call the methodology GT-inspired instead of just a GT method is because the methodology is not as rigid in its mathematical formulation as most work in the field of GT. Instead the focus is on the philosophical function and applicability of modelling using GT.

(3) An argued game-theoretic approach.
    c. The final section details the methodology for studying the QN scenario.

Chapter 3 details the results of the methodology. The results and their discussion will culminate in several lessons for the development and management of QN. The section division is as follows:

(1) The outcomes
    a. The GT model provides several possible outcomes of the quantum network case.
(2) The lessons
    a. Several recommendations for regulating a quantum network are formulated based on the outcomes from section 1.
(3) The discussion
    a. These results are discussed, and possible improvements in the methodology are suggested.

Each of the chapters features a short introduction and summary/conclusion. Only chapter 3 does not have a summary/conclusion because it is followed by a larger conclusion. In this conclusion, the recommendations and results are discussed in the context of the entire thesis. In this conclusion, the main question is explicitly answered.

Chapter 1: Quantum Technology and Quantum Networks

Opening of the Chapter

This chapter introduces the topic of quantum technology. The aim is to develop a practical understanding of QT, focusing on applications and impact instead of the physics of quantum mechanics. There is no in-depth discussion on quantum theory, but enough information to start thinking about QT in a broader socio-technical context. Technical details and fundamental quantum concepts are described to the extent that they help in understanding the novelty of QT.

This chapter focuses on quantum networking (QN), which is one of three subfields in Quantum Information Science (QIS)[4] (van Bree et al., 2023). As discussed at the end of Section 2 (p. 16), QN stands apart as a less mature field with a high potential for disruption and is deserving of further attention.

The end goal is to explore what a future quantum network could look like. The final section details a specific QN case which includes relevant stakeholders and the capabilities, impacts, and possible applications of the technology. This case is the theoretical foundation upon which Chapter 2's methodology is built.

The chapter starts with a general overview of QT and slowly zooms in on the specifics of QN and the relevance of studying interactions in a QN scenario.

S1 A (very) Brief Introduction to Quantum Technology

Talking about quantum is tough. The complexity of quantum as metaphorical *"rocket science"*, can be seen in both historical context (Grinbaum, 2017) as well as popular writing (Possati, 2024). When discussing anything quantum, one eventually needs to face this notorious reputation of quantum mechanics. Quantum mechanics herein functions as a gatekeeper of quantum technology, where you cannot start thinking about quantum technology unless you understand quantum mechanics. Current thinkers on QT consider this reputation a hurdle that should be overcome (Vermaas, 2017).

To build a workable understanding of quantum technology, it is wise to take some time to consider what *understanding quantum* means. I argue that a pragmatic technical understanding is more useful for talking about quantum technology than a fundamental understanding of quantum mechanics. This practical understanding provides some technical knowledge where needed but mostly values impact and capability over technical understanding.

Understanding Quantum

Does one need to fully understand the fundamentals of quantum physics to start thinking about quantum technologies? There are different approaches to creating understanding in such a theoretical field. The first, and most intuitive way to approach this is to start at the bottom (the fundamentals) and work our way up to the practical (applications). Taking such an understanding results in conversations about quantum mechanics before anything else. We could even go a step further and discuss the metaphysical implications of quantum mechanics,

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[4] The other two being quantum computing (QC) and quantum sensing (QS)

such as in the works of Capra (1975) and Barad (2007). Such approaches are valuable within the broader context of the philosophy of physics, but these considerations do not bring us closer to working with QT. Not everyone has the time to become a theoretical physicist or philosopher of physics, and therefore a more pragmatic approach is desirable. How can we get to a workable understanding of QT?

> *"We do not believe one can intelligently discuss what quantum mechanics means until one has a firm sense of what quantum mechanics does." - Griffiths & Schroeter (2018)*

This quote from Griffiths & Schroeter (2018) is from an introductory textbook to quantum mechanics. While their quote is about quantum mechanics (not quantum technology), I believe there is value in their framing. It seems similar to how people learn languages, where studying a language through books and theory is different from actually speaking it. One of the most common advices for learning a new language is to just start speaking it with others. This simple example shows us that there is more to understanding a field than just building knowledge from a foundation. We can translate this to understanding technology. Understanding what technology does, is about more than knowing its physics and engineering. Allow me to elaborate on this with an example from another field of physics.

One does not need to understand the fundamentals of electromagnetism to discuss the impact of computer technology. Understanding the impacts of computing technology on society does not start with a crash course on Maxwell's equations. Instead, the technology's capacity, such as worldwide connectivity and high-level calculation power can be used as points of departure. Computing technology does depend on theories of electromagnetism and this knowledge is required if one wants to engineer the chips and devices themselves. It is not true, however, that we need those theories to discuss their technological impact. Similar shortcuts can be taken with QT.

Understanding QT is not trivial but discussing it without a physics PhD is possible. Some of the apparent complexity of QT is the result of its notorious reputation, which can be overcome. The following sections detail a pragmatic understanding of quantum technology. They feature fundamental quantum theory and nontechnical descriptions of quantum phenomena where needed. The aim is to provide enough knowledge to understand what makes QT unique.

Quantum Information Science, and the Three Subfields of Quantum Technology

Talking about QT nowadays implicitly implies a specific set of technologies from the field of Quantum Information Science (QIS). These technologies are concerned with collecting, transforming, and distributing information on a quantum scale. Each of these three aspects (collecting, transforming, and distributing) has its specific subfield in QIS: quantum sensors, quantum computers (QC), and quantum networks/communication (QN) (Hoofnagle & Garfinkel, 2021; van Bree et al., 2023).[5]

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[5] Sometimes the field of quantum simulation is added to these three. (Karstens et al., 2023). Most times, however, quantum simulation is seen as an application in quantum computing.

Quantum sensing (QS) covers a set of sensors with a higher sensitivity and accuracy than classical sensors. They provide promise in the fields of metrology and potential applications in predicting earthquakes (Hoofnagle & Garfinkel, 2021; The quantum vision team, 2019). The disruptive effects of QS, however, are little compared to its Computing and Communication equivalents. In simple words, QS does things that classical sensors already do, but they do them better. Their applications include "Measurement of magnetic fields, electric fields, gravity, temperature, pressure, rotation, acceleration, and time" (Hoofnagle & Garfinkel, 2021, p. 7). The applications where QS will be useful already exist in classical sensing technology.

Quantum computing (QC) provides a new method of computation and programming. Quantum computers can perform a specific set of mathematical operations significantly faster than their classical counterparts. The fundamental principles behind QC are detailed more in the next section, but for now, the knowledge that QC does some things faster than classical computing is sufficient. Quantum computers are not yet available at a scale that would make them useful, but there are plenty of organizations working on furthering the engineering challenges that come with them. The point at which a quantum computer can outperform a classical computer, which is often called the point of quantum advantage or quantum supremacy, has not been achieved yet. Still, algorithms that can be run on a quantum computer do exist. These algorithms show signs of furthering the possibilities in Encryption, medicine, optimization problems, search algorithms, and machine learning (Jyothi Ahuja & Dutt, 2022).

Quantum networking (QN) is the quantum equivalent of classical network communication technology, such as the Internet. Like the regular internet, a quantum network is not contained in one technological device. It is a system of physical network cables, processors, senders, receivers, and large stacks of network code. Where a quantum network differs from a classical network in the way that it encodes information, which is elaborated on in the next section.

Throughout the rest of this thesis, QT will refer to these three specific sets of technologies, as this is what most communication about QT assumes. It should be noted, however, that the *information* part of QIS does remain an important aspect. This is because, the way in which these technologies collect, distribute, and transform information is what makes them fundamentally different from their classical counterparts. To understand this difference, some elaboration on quantum mechanics is needed.

S2: Putting the I in QIS

Information in QIS is different from how we classically understand information. This is because, at a quantum scale, information carriers behave differently than at a classical scale. In quantum mechanics, particles can show the behavior of both particles and waves. Understanding and exploiting these properties allows for new engineering opportunities. This is exactly what QT does. QT manipulates particles at a quantum scale in such a way that we can do new things with them compared to their classical counterparts.

What is Quantum Information?

All information on classical networks and computers is encoded in bits. Bits are the smallest pieces of information that a computer can work with. A bit can carry the value of 1 or 0. These 1's and 0's are imperceivable during most modern computation work because a lot happens to these 0's and 1's before they become interpretable for most computer users. Even though they remain unseen most of the time, all information on computers and in internet communication boils down to 1's and 0's.

Quantum information is different. Instead of encoding information in a bit, quantum information uses a qubit. Qubits have two properties that make them fundamentally different from regular bits. The two important properties to understand their difference are superposition and entanglement (Textbox 1-2). [6]

Quantum Property 1: Superposition

In quantum mechanics, atoms do not behave like little marbles. This is because, at a quantum scale, particles can show both particle-like and wave-like behaviour. What specific behaviour they show depends on and whether (and if so, how) they are being observed.

This is different from classical physics. When taking a classical measurement, such as measuring the speed of a car, the measurement itself will not influence the thing being measured, in this case the speed of the car. In quantum information, however, the measurements influence the thing being measured.

When a particle is prepared to contain specific information, measuring the particle will change the contents of its information. As will be discussed later, this has some large implications for network communication.

Superposition in quantum information therein means that a qubit is not in either a 1 or 0 state but can be in between these states. Only when the particle is observed, the qubit will take on a specific state. Due to the nature of superposition, working with qubits is fundamentally different from classical bits.

Quantum Property 2: Entanglement

In quantum mechanics, objects can be manipulated in such a way that their state becomes intertwined. This is called entanglement.

When two particles are entangled, the outcome of measuring one particle will inevitably be tied to the outcome of measuring the other particle (see Figure 1)

Textboxes 1-2: Quantum Properties

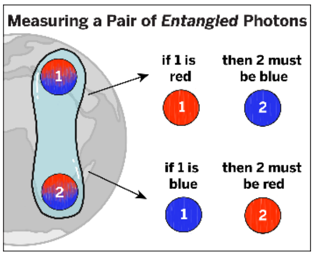

Figure 1: Retrieved from quantumatlas.umd.edu/entry/entanglement

In its current state, quantum mechanics has not figured out why particles behave in this way. Through experiments, however, we know that they do. Quantum Technology exploits these properties by recreating the specific conditions at which the laws of quantum mechanics become relevant. The following section details some of the applications that can come from this exploitation.

Applications and Impacts of QT

Most QT applications are still in development. Because of this, not all possible applications are known. New applications could be discovered in the future. There are, however, specific fields where it is known that QT provides new possibilities or advantages over current technology. The following sections introduce some of the general applications that QT has and provide some indication of the fields that they will impact.

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[6] An often-used example for explaining superposition as a spinning coin, which is both on heads and tails at the same time while spinning (Hoofnagle & Garfinkel, 2021; The Quantum Vision team, 2019). Only when observing (catching the coin) does it become clear which side is up. This is illustrative for measuring a particle's spin, which is probabilistic and only becomes rigid when one observes it.

Quantum Cryptography.

The more widely known applications of QT are in cryptography, or rather against cryptography. Cryptography is the field concerned with encoding and decoding information. The specific part of encryption that QT will impact is key distribution. Encrypted information is safeguarded with a mathematical key. If someone were to intercept transmitted data, the contents of the information look like random nonsense to any third party without the mathematical key. One of the most well-known encryption methods (RSA) creates keys through the specific mathematical problem of prime multiplication. Prime multiplication is mathematically simple to solve in one direction, but notoriously complex the other way around. QT is proving to be a threat to this form of encryption.

Through the use of a specific algorithm (Shor's algorithm), quantum computers can solve these complex mathematical problems significantly faster than classical computers. This means that actors with a quantum computer could collect encrypted information and use their quantum computer to decrypt the contents of the message (De Wolf, 2017). One sign of the potential for these disruptive effects is the fact that larger geopolitical parties are practicing a *Save now, decrypt later* approach, where they are saving encrypted information now to decrypt it later when quantum systems would allow this (Townsend, 2022). There are classical encryption methods that protect against these encryption methods (Barker, 2021), but these are not widely used yet.

Quantum cryptography, however, is not only about decrypting data. Quantum communication systems allow for a novel way of distributing encryption keys. As described in Textbox 1, observation plays a key role in quantum information systems. Quantum Key Distribution (QKD) makes use of this by distributing keys in such a way that there is no mode of interception. If a third party were to intercept a quantum key, the key would be changed in the process. This change would allow the two communicating parties to know that someone is interfering with their communication. This mode of key distribution is resistant to Shor's algorithm because it is not dependent on prime factorization.

Quantum Algorithms

Because quantum computers are fundamentally different from classical computers, they require a different method of operation. This means that coding on a quantum computer is different from coding on a classical computer. This fundamental difference means that quantum computers can perform some mathematical computations faster than classical computers. Known quantum algorithms feature improvements in search and optimization algorithms (De Wolf, 2017). Shor's algorithm, as described in the previous section, is also one of these algorithms.

The thing about these algorithms is that their development is an ongoing process. There could be new algorithms discovered in the future with applications that provide additional applications. Shor's algorithm, for example, was originally developed by Peter Shor in 1994 (Shor, 1994). Only recently, 30 years after Shor's original paper, Oded Regev discovered an optimization in the algorithm (Regev, 2024). This shows that even after decades of research, new algorithms and optimizations can still pop up.

Distributed Quantum Computing

One of the main pursuits in quantum computing is scaling the number of usable qubits. There are some strong engineering challenges in the creation of these computational systems. A way of overcoming some of these challenges would be to link several smaller quantum computers.

Effective linking of quantum computers can happen through a quantum network system (Awschalom et al., 2021; Singh & Bhangu, 2023). This means that, through a quantum network, different actors could combine the computational power of their individual quantum computers (Singh & Bhangu, 2023).

Distributed computing already exists in high-performance computing, but there is something special about distributed quantum computing. Distributed quantum computing allows for, what is known as blind computing. Blind computing prepares and processes data in such a way that a quantum computer host cannot keep track of performed calculations (Broadbent et al., 2009). This is, again, due to the nature of quantum information. If the information is prepared in a certain way, there is no possible method for a third party, nor the host of the quantum computer to get access to the information. This is because observing the data would alter it and destroy/interfere with the computational operations. Only the person who prepared and received the final computational results can access the information.

For classical systems, there is a constant need to ensure that information remains private. Anonymization remains a significant hurdle in data collecting and processing. While some of these concerns remain, the application of blind computing can overcome part of the challenge in secure data processing by making it impossible to retrieve data from a physical computation system during or after processing.

Other applications of distributed quantum computing include solving problems in classical distributed computing (Denchev & Pandurangan, 2008) and clock synchronization. All these applications will have an impact on several different fields. Below are three examples of fields that will eventually benefit from these applications (Textbox 3-5).

Application field 1: Simulation (Drugs and Materials)

Material simulation classically models the physics behind a system with mathematics. The idea of quantum simulation is that, instead of imitating quantum physics with binary operations, one would use the quantum properties of a qubit to replicate the quantum system itself. The idea of simulating systems using a quantum computer was originally proposed by Richard Feynman (1982).

This would allow for control of the smallest model parameters and can allow for revolutions in drug design and Materials Science (Karstens et al., 2023).

Application field 2: Astronomy

Modern radio telescopes often consist of multiple antennas. To create an image, the signals of these antennas need to be combined and calibrated. There is a possibility of linking these telescopes through entanglement (Nichol et al., 2022), which could overcome synchronization problems. There is also a possibility for improving calibration through a quantum algorithm (Leijnse, 2024).

Application field 3: Military

Secure communication and intelligence gathering are key capabilities for military institutions. Therefore, applications 1 and 3 are strongly intertwined with military applications of quantum technology. The applications, however, go beyond just these two.

In a 2021 review, Michal Krelina details several ways in which quantum technologies can serve military applications. These include underground mapping technology, chemical detections and simulations, situational awareness and internal navigation of missile systems (Krelina, 2021).

Textboxes 3-5: application fields

For some of these applications, like the synchronization of telescopes in astronomy, the impacts will mostly be contained in the application field itself. Others, like Shor's algorithm, will have impacts beyond their respective field (De Wolf, 2017). Currently, there are no regulations in place to control these impacts. Therefore, there is a need to start translating their technical capabilities to social impacts and build good practices around QT usage from this.

The ethical, legal, and social disruptions of QT as a whole are already being explored (Coenen et al., 2022; DiVincenzo, 2017; Grinbaum, 2017; Kop et al., 2023), but due to the differences in each subfield's capacities, there is a need to consider them separate as well (Coenen & Grunwald, 2017). QC, for example, has already received exploration into both its technical capabilities (De Wolf, 2017) and in ethical, legal, and social aspects (Perrier, 2022; Possati, 2023). QS is considered a more mature technology and its applications and impacts are better understood than the other two (Hoofnagle & Garfinkel, 2021). QN therein stands apart as a less mature field with a high potential for disruption and is deserving of further attention. Because of this, the remainder of this thesis focuses on QN technologies.

S3 Quantum Networks and Actor Behavior.

QN stands apart from QC and QS because networks are not a singular technology. In the same way that a single router does not make an internet, one needs multiple devices to create a quantum network. A network connects beyond just devices. Networks are all about connectivity, both in connecting different devices, and connecting users through these devices. Regulating a network, therefore, requires knowledge about both the technology itself and the interactions between its users.

To understand how we can interpret the dynamics and capabilities of a quantum network, the following section explores (1) the physical infrastructure of a QN, (2) what specific actors will be involved in operating a QN, and (3) how actors can make use of a QN.

Connecting Devices (Physical Infrastructure)

In terms of infrastructure, one can interpret a quantum network akin to classical communication networks like the Internet. Even though terminology like *The Cloud* might lead you to think otherwise, the internet does not exist in the air. It is a system of physical network cables, processors, Wi-Fi routers, Wi-Fi receivers, cell towers, large stacks of network code, and much more. A quantum communication system will also consist of many different devices.

The bare minimum components that can make up a future quantum communication network are (1) physical connections and (2) hosts (see Figure 2). Physical connections will most likely be in the form of optical cables or satellites (Wehner et al., 2018). Hosts are actors that can prepare and send quantum information (Wehner et al., 2018). Devices that prepare quantum information can be quantum computers or quantum sensors, and these devices can function autonomously or be operated by a human. A quantum network could therein feature quantum computers and quantum sensors as parts of the network. To make use of the network through distributed computing however, even a device that can prepare and read single qubits is sufficient (Broadbent et al., 2009).

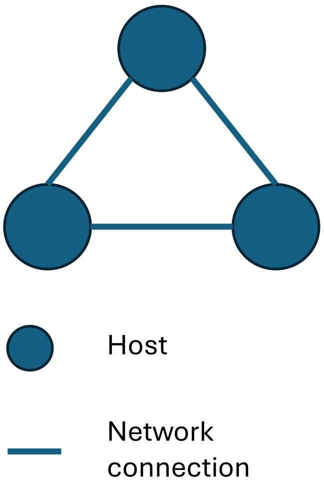

Figure 2: Minimal Quantum Network

Of course, this is a simplified version of a full quantum network. There are some complexities to constructing a quantum communication. One such thing is the physical loss of quantum information over longer distances.

Transporting entangled particles over an optical fiber comes with degradation (Simon, 2017). Disturbances, such as temperature, can cause the loss of quantum information. To scale a quantum network to longer distances, “intermediate nodes called quantum repeaters are necessary” (Wehner et al., 2018, p. 2). The purpose of a quantum repeater is to create several points of entanglement between two nodes of the network. Because the loss of quantum information over optical fiber scales exponentially, placing these quantum repeaters in between the hosts would significantly decrease the loss, making communication over longer distances possible (Wehner et al., 2018).

There are more artifacts besides quantum repeaters needed for these systems. This includes, for example, devices that can act as quantum memory (Awschalom et al., 2021). Also, as mentioned before, a quantum network can include other quantum devices, such as quantum sensors. When we take these complexities, and the possibility of connecting QS and QC devices, we get a more complex-looking system, such as visualized by Awschalom et al. in Figure 3.

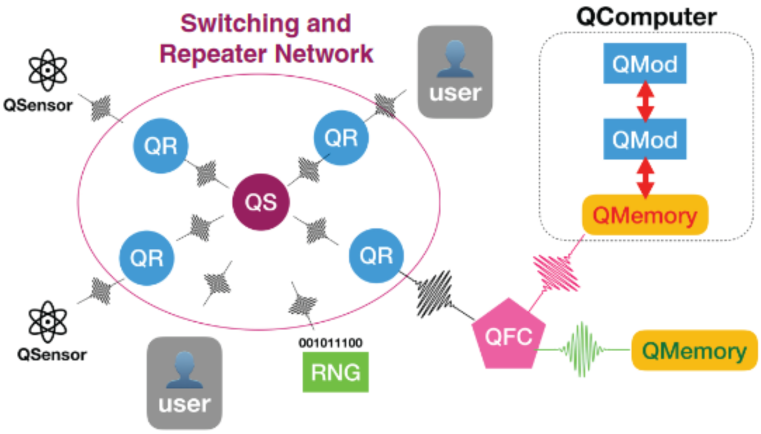

FIG. 1. The broad role of QuICs in quantum information technology. QS, quantum switch; QR, quantum repeater (a device that can relay an entangled state from one set of qubits to a distant set without physically sending an entangled qubit the entire distance); QMod, modular quantum processor; QFC, quantum frequency converter; RNG, random-number generator. The QuICs are indicated by bold red arrows or by wave packets representing photons.

Figure 3: Example of a quantum network connecting several users, quantum sensors and quantum computers (Awschalom et al., 2021)

Many of these devices can be replaced with non-quantum equivalents. By integrating these devices, some of the advantages of a quantum system will be lost. Each non-quantum device will act as a point of vulnerability for QKD or blind computing. Therefore, non-quantum devices in the system require physical safeguarding. The secrecy of QKD, for example, is compromised because a non-quantum repeater would have to translate the quantum information to classical information. This means that there is a point at which the information being sent could be intercepted.

It should be noted that, even in a quantum network without any non-quantum components, information still can leak out of the system. This partially depends on the construction of the system, such as the integration of full-quantum repeaters and other quantum-specific devices. But at large, the important thing to consider is the other actors in the system. Human failure remains an important factor in these security systems. At this point, it makes sense to move beyond the technical capabilities of the system and start considering the users of the system.

Connecting People

In their current state, quantum systems are notoriously difficult to operate. Modern quantum computers (such as the one in Figure 4), are more like medical equipment than slick computational chips. All of the equipment one sees in these crown-jewel-like devices is used for keeping the Qubits stable. The actual Qubits of a quantum computer are small and unobservable to the naked eye. All the other systems surrounding it are built to keep the qubits stable. Consider it like a cooling fan in a regular computer, but the fan would make up 99.99% of the computer. Operating and maintaining these systems is costly, and therefore it is likely that these processors will mostly be available for larger organizations and governments instead of individual customers.

Figure 4: Image of a quantum computer (collected from: reddit.com/r/pics/comments/9win14/ibm_q_quantum_computer_on_display_at/)

It is likely that over the upcoming years, these systems will shrink in size, but it is unlikely that they will be owned by any individual users/citizens. This is because the advantages that quantum computers provide are not useful to all computing applications. Quantum computers do not provide a general scale-up in computing power, but an advantage in specific mathematical calculations. Therefore, they are unlikely to replace classical computers but instead be used in a centralized and distributed manner. This is like High-Performance-Computing (HPC) systems. These systems are also centralized, and computation on these machines is distributed from central organizations.

The different application fields discussed earlier (Textbox 3-5) indicate the kinds of organizations that will be interested in partaking in a quantum network. Hospitals, Militaries, and research institutes are likely contenders. Especially larger organizations and nations would benefit from the security advantages. A sign of growing interest in these technologies is the growing number of national programs interested in growing knowledge and technical capacity on QT. Examples include EuroQCI, Quantum Spain, Quantum Delta NL, and Quantum Australia.[7]

There are also reasons why these actors would want to connect their computational facilities. As detailed before, a problem in developing quantum systems is that scaling these systems is difficult. For actors to reach a quantum advantage (term explained at the end of section 1), connecting several small-scale quantum computers is a quick way to overcome the engineering challenges in increasing the number of effective qubits.

In brief: it is likely that participants in a quantum network are larger institutions over individuals or smaller organizations. This is because (1) larger organizations are more likely to benefit from the specific advantages of quantum computing, (2) the systems are large and expensive in maintenance and (3) partaking in a network allows them to increase computational power and possibilities without having to upscale their computational facilities.

How will QN Systems be used?

The previous two sections detailed the technical capabilities and the likely candidates. This chapter aimed to build a case study that can be used to study the interactions in a QN. Because of this, it is wise to attempt some form of specification in how specifically the actors will be able to use the system. The following section clarifies some of the interactions that can take place on a regular network and translates these interactions to a quantum network.

There are many possible ways in which actors can make use of network technologies. For classical networks, like the internet, one can go into endless specifications. Users can chat, hack, play games, consume media, distribute media, spy, research, compute remotely, farm cryptocurrency, order drone strikes, set up pyramid schemes, sell art, make art, launch missiles, and so forth.

For now, there is no need for a complete classification of all these activities. However, there are some high-level differentiations we can make between different types of activity. If we set up these classifications for the classical internet (Textbox 6-9), which is more intuitive than QN, we can start translating this behavior to activities that make QN interactions unique (Textbox 10-13).

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[7] At the moment of writing, all of these are active projects from the European Commission. (SOURCE: commission.europa.eu/projects)

Behaviour 1: Collaborate

Actors sharing resources to further common goals. This can go through communication but can also involve sharing, for example, computational resources or collaborating on a shared databank. Often goes paired with communicating but it is not required that one party's information be shared with the other. An example of this could be remote computing where the hosting party does not care for the information specifically.

A subcategory of collaboration could be hosting/outsourcing: *Here one party provides services in exchange for money/information. Services such as Google and Nvidia already do this for classical computation.*

Behaviour 2: Communicate

This entails actors attempting to transfer information between each other. This can be informal conversation via text channels, video calls, or data transfers.

Behaviour 3: Spy

Attempts to intercept/decode information from a different party without the other party knowing that this information is in your hands.

Behaviour 4: Attack

Sabotage or destroy information or infrastructure, hereby limiting another party's possibility of communicating. This can come in both the form of an attack on physical infrastructure, such as laying down satellite communication, or attacking an internet host/cable network, or a digital attack such as a DDoS attack which attempts to overflow a communication system with useless requests. Because of the direct implications that such an attack can have, both a physical and digital attack can have the same severe effects (Taddeo, 2012).

Textboxes 6-9: Behaviour types in a classical internet

These different behavior categories (superficially) fit '*most of the things that one can do on the internet'*. We can use these classes to explore how actors can behave in a QN. Translating these behavior types also reminds again that "a quantum internet is not meant to replace classical communication but rather to supplement it" (Wehner et al., 2018). This means that QN hosts will not fulfill all behaviors that we know from the classical internet. Instead, the QN system can replace some of the activities from the classical internet and introduce some new possibilities.

What is interesting about these possibilities in QN specifically is that they can be performed without oversight. This is because of the possibility of blind computing. If actors decide to share

Behaviour 1: Collaborate

Share computational resources through distributed quantum computing.

Behaviour 2: Communicate

Securely connect different actors through QKD privately distribute information.

Behaviour 3: Spy

Make use of Shor's algorithm to decrypt information.

Behaviour 4: Attack

Make use of computational resources to calculate strategic military advantages, improve weapon development, or simulate biological weapons.

Textbox 10-13: Behaviour examples in a quantum network.

their computational power, they can make use of each other's resources without any knowledge or supervision about the specific calculations happening. This includes military and intelligence-gathering practices.

There is a tension here. On the one hand, it makes sense for actors to connect their quantum systems, because fully developing a quantum computer themselves will be a costly and technically complex endeavor. On the other hand, connecting blindly to other actors might result in the abuse of the system for malicious purposes. This tension and the search for regulations that can help in achieving these goals is the focus of the case study.

S4 The QN Case Study

This section regroups the information from the previous sections into a workable case. Both the complexities of QT and the involved actors in the essential aspects of studying interactions between QN hosts are briefly summarized. Even though the specific methodology for the case study is developed in Chapter 2, this section outlines the basic parameters that remain in consideration for the case study.

The aim is not to build a *real* case. This means that there are no geopolitical considerations or real-life projects taken into consideration. Instead, the aim is to keep it a *realistic* one. How the imagined case can play out is defined by the real capabilities of QT. For QN specifically, this means focusing on the capabilities that relate to connectivity.

The section details (1) the actors in the case (the players), (2) how they can interact, and (3) the decisions they can make in these systems.

The Players

As discussed in the previous section, likely candidates for hosting a quantum system are large organizations. This is because quantum computers only provide advantages in a specific subset of applications, and hosting it is a costly endeavor. Research or medicine institutes, government bodies, or military organizations are likely candidates in these fields.

Therefore, the case considers the main hosts (or players) as larger organizations that own a certain amount of computational power. They can use their computational power in whatever way they desire. Their computational power can be shared with other actors, such that these other actors can make use of the computational power as well. Players benefit from more computational power, as this brings them more quickly to a quantum advantage over classical computation. These organizations must make concrete decisions and decide whether they'd like to share their computational resources with others.

The Interactions

Actors can decide to share their computational power by connecting to the distributed computing network. When actors decide to share computational power, they both benefit from the shared connectivity. This connectivity needs to come from both ways, so if one of the actors decides to break the connection, neither is able to access the other's computational power.

Apart from a qualitative increase in computational power, there are also other benefits from connecting to such a system, such as being able to make use of a QKD system or using it for synchronization of research instruments like astronomy equipment.

If agreed upon by all actors, the distributed computation can happen through blind computing. This allows for computation without oversight from the other hosts. These interactions are made possible because of the blind computing that a quantum system can offer. This blind computation is only possible if the full system consists of quantum equipment. If there is any non-quantum component in between, the blind connection is compromised at that specific point.

The Decisions

As stated before, the actors must decide between sharing computational power or not sharing. How this decision is made specifically shall be the focus of the next chapter, in which the study methodology shall be explained more thoroughly. There is a specific aspect, however, that requires some elaboration.

The kinds of connections that can be established between quantum systems have been explored before by Possati & Vermaas (Forthcoming). Their paper on the rationality and morality of connecting quantum computers, detailed specific options in which actors could connect their systems. They differentiated between three scenarios, a blind connection, a governed connection, or no connection (Possati & Vermaas, Forthcoming). The contents of their study and mine are similar since both explore the outcomes of linking quantum systems, so for complementarity's sake, it would make sense to take the same approach.[8] There are two ways in which these scenarios are tweaked.

First, I distinguish between a blind connection and a governed connection as two different scenarios. This is because choosing between one or the other is not as simple as flipping a switch. Blind quantum communication requires a specific network protocol (Broadbent et al., 2009), and switching from one protocol to another requires a fundamental redesign of the network. Therefore, taking blind connection and governed connection as two separate future scenarios and studying the dynamics that can take place after these systems have already been constructed makes more sense. The actors' decision is then whether they'd like to retain the connection or stop the connection. This is further elaborated in Chapter 2.

The second change concerns the dual-use nature of the quantum system. Blind quantum computing provides a unique opportunity to use another's computational resources without knowing what is happening in their system. The connection can be used for both good and bad without anyone's knowledge. This blind connection can be used, for example, in using private patient data in computations without having to open it up to partners in the system. On the other hand, blind connections could also be exploited to decrypt intelligence data from other

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[8] Because of the strong connection between the work from Possati & Vermaas and this thesis, it is useful to clarify the difference between their work and mine.
Possati and Vermaas (Forthcoming) go beyond the analytical and discuss the morality of connecting quantum computers. They, for example, detail the moral trade-off between transparency and autonomy in deciding to share or not share a connection. Because the remainder of this thesis focusses on a specific conceptual experiment in using GT modelling for the assessment of QN, this focus on morality will not be as explicit.
The strongest similarity is in the analytical setup. Both my study and theirs, considers connecting quantum devices as a problem in strategic thinking. Actors can decide to connect or not connect their computational systems. As will become clear in Chapter 2, I use a specific methodology inspired by GT for this, while their analytical approach is less explicitly connected to a particular field (besides philosophy and ethics).

organizations. The first medicine example could be valuable for the entire field of medicine, while the second is a selfish use of resources.

To explore this tension, I'd like to add the specific intentions of actors as a parameter in their decision-making. From this, we can see what specific dynamics and decision-making dilemmas arise from the potential abuse of QN.

Closing of the Chapter

This chapter worked through ***the development and management of quantum networks***. The aim was to establish sufficient technical knowledge on QT and QN to build a potential future case. This meant not only establishing the fundamentals of QT but also considering what it means to understand quantum. By building a sufficient understanding and working through examples and applications, the fourth section built a future case that includes the relevant actors and the ways in which they can interact through a QN. This case is used to study QN throughout the remainder of the thesis.

By abstracting the field of QN to a specific case, some of the technical details of the technology were lost. For example, the different application fields, as described in Textbox 3-5, have been abstracted to examples of dual use. Therefore, the remainder of the thesis has little consideration of each of these specific subfields, and the focus remains on the technology itself. At the same time, the case study retained important capabilities of QN, such as accounting for blind computing. Because the next chapter is concerned with a wholly different field, this focus is needed to prevent bloating.

Chapter 1 has set the stage for "what will be studied", namely a possible future QN case. The next question to answer is "How we can study this QN case". Chapter 2 conceptualizes a methodology for this. This means that the contents of Chapter 1 are now put on the back burner until they are needed again at the end of Chapter 2.

Chapter 2: A Game-Theoretic Approach to Quantum Networks

Opening of the Chapter

This chapter aims to build a methodology exploring the QN case from Chapter 1. The methodology is inspired by the mathematical field of game theory (GT). To argue for the validity of the approach, the chapter first evaluates GT as a field and argues that, when approached in the right manner, GT can serve as a useful modeling tool for exploring the QN case.

GT is a large field. With its roots in 1944, when John Von Neumann and Oskar Morgenstern brought forth its general mathematical formulations, it now finds its twigs in all sorts of fields (Von Neumann & Morgenstern, 1944). Most of its fundamental material concerns mathematical calculations and modeling, but its applications have permeated broadly through the (social) sciences. Modern GT covers applications in behavioral economics (Chou et al., 2017; Samuelson, 2016; Wheeler, 2020), but also technical fields such as network security (Han, 2012) and peer-to-peer energy trading (Tushar et al., 2019). This chapter explores which specific parts of GT can serve in working through the QN case.

The chapter begins by evaluating GT as a modeling tool. As discussed in the second section, there are different understandings of what GT can and should be used for. Instead of discussing the entire field, I argue for a specific approach and build the validity of this approach by discussing relevant parts of the field and elaborating through examples. The overall structure of the chapter is as follows.

(1) An introduction to the field of game theory.
    a. Description of GT's history.
    b. Discussion on the use of GT.
(2) Applications of GT.
    a. Discussion about the differences between normative and descriptive models.
(3) Description of the methodology for studying the QN case.

S1 A (very) Brief Introduction to Game Theory

GT stems from the field of Decision Theory (DT). DT is "the theory of rational decision-making" (Peterson, 2017, p. 1) and "is concerned with the reasoning underlying an agent's choices" (Steele & Stefánsson, 2020, p. 1). The field of DT covers the most trivial decisions (*what to have for breakfast?*), as well as terribly complex ones (*is democratic voting a fair process?*). DT formalizes the components present in decision-making and turns these components into objects of analysis. DT is therein a formalization of choice, options, outcomes, probabilities, risk, and strategy, (Peterson, 2017) but also less rigid aspects like emotions and biases (Morelli et al., 2022). DT is a broad interdisciplinary field and receives work from philosophy, psychology, neurology, and politics (Peterson, 2017). Because of this broad, interdisciplinary nature of DT, it features several subfields that focus on different parts of decision-making processes. GT is one of these subfields.

What sets GT apart from DT is that it is concerned with "situations in which decision-makers interact" (Osborne, 2004, p. 1). In GT, the outcome of a decision is not the consequence of one decision-maker but is influenced by other independent decision-makers. A simple example of interacting choice is a game of rock-paper-scissors. In rock-paper-scissors, both parties try to predict what the other will do and adapt their choice based on this prediction. GT assumes that these considerations (predicting the behavior of other parties), can describe the rational behavior of all involved actors. Actors are therein assumed to have the following characteristics (Bonau, 2017, p. 1).

A) Actors choose the outcome that they believe benefits them the most (optimization).
B) Actors change their behavior based on other's decisions (strategic thinking).
C) Players adjust their decisions and beliefs until they are mutually consistent (equilibrium).

Actors in a GT scenario optimize and adjust their strategic thinking through the pursuit of utility. Utility is a quantified version of the actor's benefit. Outcomes that are more desirable for a specific actor have a higher utility. For a game of rock-paper-scissors, this would mean that winning the game would have a higher utility than losing. Therefore, the actors in the game consider which strategies are most likely to get them to win from their opponent, and therefore receive the most utility. What specific form or value utility takes, depends on the specific scenario that one tries to model.

GT is amendable as a mathematically embedded and expansive field. The fundamental methods of GT are established and there is a large quantity of literature describing its content and modes of calculation (e.g. McCarty & Meirowitz, 2007; Osborne, 2004; William Spaniel, 2013; Zamir et al., 2013). These methods often go through the same mathematical foundation with different didactical approaches.

What should GT be used for?

While GT has an extensive library of tools and methods, it remains to be questioned whether it is useful as a modeling tool for all decision-making scenarios. As with all modeling practices, the purpose and contents of the model should be in line. Larry Samuelson (2016) describes a useful interpretation of GT models. In, what he calls *An Instrumental View of GT*, GT models should not be taken as a "literal description of the situation of interest" (Samuelson, 2016, p. 109). Instead, they are a "deliberate approximation, designed to include important aspects of the interaction and exclude unimportant ones" (Samuelson, 2016, p. 113). This means that, as with any model, it is important to consider whether a model's assumptions are adequate for the situation it tries to model.

Basic GT assumes optimization and strategic thinking as the most important modes of thinking for its actors (Bonau, 2017). Such assumptions do not apply to any scenario. Imagine, for example, choosing between different options on a restaurant menu. Here, often people consider their personal taste over optimization and strategic thinking. Therefore, GT is not a useful modeling tool for these situations. In other cases, it does make sense to use GT as a modeling tool.

Example 1: The Prisoner's Dilemma

In the prisoner's dilemma, two people are arrested for a mutual crime and independently questioned. The goal of each prisoner is to minimize their own sentences. The police ask them whether they are willing to testify against the other prisoner. Their options are to stay silent (cooperate with their fellow prisoner) or to testify against the other (betray their fellow prisoner). If both stay silent, each faces a short sentence. If one talks and the other stays silent, the silent one faces a long sentence and the other goes free. If both testify against each other, each gets a medium sentence.

The tension in the prisoner's dilemma is that betrayal always improves a player's own benefit. If both prisoners take this approach, however, they are both worse off than if they had taken care of each other. To make an informed decision, each prisoner must consider their expectations of the other prisoner.

Textbox 14

The prisoner's dilemma, as explained in Textbox 14, has embedded itself as a cornerstone example of GT. It is featured as a prominent example in GT textbooks (Nordstrom, 2020, p. 57; Osborne, 2004, p. 14; Peterson, 2017, p. 236; William Spaniel, 2013, p. 9), and is often presented in popular communication on GT.[9] It works great as an example for explanation, and therefore it has become a cornerstone example of what GT *is*. GT *is* about interacting choice, and the prisoner's dilemma neatly illustrates how other's choices can influence your outcome. What the dilemma lacks, however, is showing what the model *is used for*. Let me elaborate on this distinction between what GT *is* and what it *is used for*.

GT is everything this chapter has described thus far. GT contains methods, examples, textbooks, teachings, and a lot of mathematics. Without context, GT is a study of math and logic. The prisoner's dilemma is an example of this. It shows us an abstract situation where outcomes are determined by a specific set of conditions. When inputs (Choices from P1 and P2) are provided, we can follow logical steps to come to the outcome (sentence length). We can see this as a mathematical model without a clear application.

What GT is used for, concerns the application of the model. The prisoner's dilemma is an abstraction, but what it specifically tries to abstract is not given. We could interpret it as a model for real-life interrogations. The model gives us a reason partners in crime would confess against each other, namely that they personally would be better off betraying the other. Whether this is a suitable approach however is questionable. The model, for example, does not include the pressure that interrogators can put on the criminals and the level of trust between the prisoners. This shows us that, while the prisoner's dilemma is constructed with the narrative of two prisoners, it does not necessarily help in explaining their true behavior. To understand what the prisoner's dilemma and other GT models try to do, it is useful to differentiate between different kinds of models.

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[9] See for example (The Game Theorists, 2024; Veritasium, 2023) or popular media, like the *split or steal* section from the British game show *Golden Balls*.

S2 Types of GT Models (Normative vs Descriptive)

An important aspect when applying GT as a modeling tool is understanding the difference between descriptive and normative models. The difference between descriptive and normative models comes from the field of DT (Peterson, 2017) and can be understood as follows. Descriptive models attempt to understand what lies behind a real-world decision-making case and normative models focus on what *ought* to lie behind human decision-making. Understanding their differences can help in understanding how to apply GT.

Descriptive models “seek to explain how people actually make decisions” (Peterson, 2017, p. 3). In a descriptive model, the aim is to simulate real-world decision-making. A descriptive model therein assumes that the parameters included in the model are also the parameters that the modeled actors would consider in the real world. If the outcome of the model matches observations in the real world, the model can be used as an explanatory device for the real world.

Normative models aim “to yield prescriptions about what decision-makers are rationally required – or ought – to do” (Peterson, 2017, p. 3). Normative models of decision-making do not have to model human decision-making but can serve as an exploration of strategy and different outcomes.

There are examples of both descriptive and normative models in GT. Examples 2 and 3 (Textbox 15 and 16) explore a descriptive and normative model respectively.

Example 2: Schelling’s Model of Human Segregation

Thomas Schelling’s model of human segregation (Hankins & Vanderschraaf, 2021; Sullivan, 2022) is an example of a descriptive model. The model aims to explain the phenomena of segregation by testing to what extent rational actors order themselves based on neighbor preference. In this model, actors are programmed as squares in a grid. The squares are programmed to desire a specific percentage of squared around them to be of the same color. If this percentage is not achieved, the square moves to the nearest empty (white) square. Several versions of the equilibrium state (the state in which no square has the desire to move anymore) are shown in Figure 5. The percentage threshold states the minimal % or equal squares that a square *wants* to have next to it.

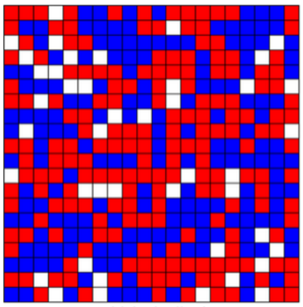
The model shows that giving each colored space the “preference” to have a certain percentage of similar color next to it, results in the board migrating to a “segregated” state. The aim of the model was to identify “a possible causal mechanism of segregation” (Sullivan, 2022, p. 5). In these descriptive models, actors are given a certain set of *behavior* traits. When the model shows signs of correspondence with the real world, these traits are taken as *likely-to-be-the-case-in-the-real-world-as-well*.

Example 3: The tragedy of the Commons & Common Pool Resources

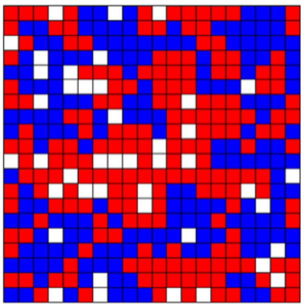
The tragedy of the commons is a well-known thought experiment in economics and ecology and serves as an example of a normative model. It is concerned with situations where choices of short-term benefit for the individual result in long-term harm for everyone (Hardin, 2009). In the experiment, actors have the option to take from a Common Pool of Resources (CPR) which replenishes over time. If only one of the actors takes more than their share of resources, the impact on the CPR is limited, but if every actor decides to do the same, the CPR becomes exhausted.

The tragedy of the commons translates, for example, to the exhaustion of greenhouse gasses. Overuse of fossil fuel benefits one by providing usable energy, but in the long run, degrades the environment for all populations and deplete the finite resource faster than nature can regrow.

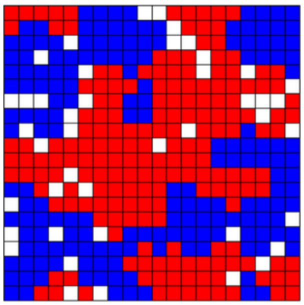
Textbox 15 and 16



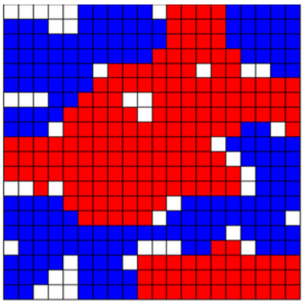
a. Initial Distribution



b. 20% Threshold



c. 30% Threshold



d. 50% Threshold

Figure 5: Schellings’ Segregation Models (Hankins & Vanderschraaf, 2021)

The demands for descriptive and normative models are different. Descriptive models represent the actors’ decision-making processes. Descriptive models require arguing that real-world actors have the same considerations as the modeled actors, or that the outcome of the model matches the outcomes of the real world. From these models, predictive and explanatory conclusions can arise. Normative models are used to explore the dynamics and strategies between different actors in an abstract scenario. Normative models require arguing that the abstraction fits the scenario that it tries to represent. Each of them has a different purpose. Descriptive models can help predict and regulate behavior while normative models can show us potential future scenarios and potential issues that might arise from a situation. The distinction between descriptive and normative is not a definitive differentiation in GT models, but understanding the difference helps in fitting a GT method to the QN case.

How, then, do we translate our QN case into a workable and useful GT model? There is not one singular answer. Depending on the construction of the model, different uses and applications can emerge. The QN case aims to explore how a QN scenario can develop. Keeping this aim in mind allows for the construction of a suitable approach.

S3 A Game-Theoretic Approach.

This section constructs a Game-Theoretic approach to modeling the quantum case. The first section argues for a suitable approach through the distinction between descriptive and normative models. The approach is compared and complimented with a similar case of a normative model applied to a real-world scenario (Textbox 17). The subsequent sections detail GT-specific aspects such as the form of the game, the mechanics, and related actors. All these specifications allow for *playing out* the QN case, which is the content of Chapter 3.

Descriptive vs Normative.

The aim is not to build a *real* case but to keep it a *realistic* one.[10] The case study, therein, aims to gain insights into the dynamics between actors in a possible future QN system. To achieve this aim, a normative model would be more suitable. Allow me to explain why.

A descriptive model requires that the model considers the same parameters as the actors being modeled, or that there is an outcome scenario to compare the model to. The segregation model (Textbox 15) did this by incorporating the desire to have similar neighbors into its model parameters. Because the outcome of the model was a segregated checkers board, the inputs were validated as a possible reason for real-world segregation. The model was a means of verifying whether a specific quality (wanting to live next to similar others) could be a cause of segregation. This is not what we desire to do with the quantum case. There are no real-world cases of a full-scale operatable QN, so therefore there are no practices to verify.

The aim was to explore the possible ways in which QN systems could develop. Normative models, such as the tragedy of the commons (from example 3), are especially suited for this. The tragedy of the commons, when applied to the case of global warming, shows different ways in which situations like the climate crisis can develop. Conclusions can be drawn from such abstractions, such as the need to regulate and control the exploitative consequences of climate pollution and fossil fuel usage.

Example 4 (Textbox 17) explores a case where such a normative GT model is used to explore different conceptions of fairness w.r.t. greenhouse gas emissions. Megan Blomfield (2013) brings specific issues and challenges to light with the climate crisis through building an intuitive decision-making model, inspired by the tragedy of the commons. This is what a normative GT framework can provide us. Pointers for going forward in these problems and understanding the dynamics at play.

Focusing on a normative model is therefore suitable to our quantum case. It allows for exploring different future scenarios and actor strategies. This means steering away from the descriptive model with explanatory and predictive capabilities. Chapter 3's discussion (p. 41) discusses the

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[10] Repeated from the beginning of Chapter 1, Section 3.

possibilities of integrating descriptive aspects for prediction and explanation, but for now, these aspects remain out of scope.

Example 4: Common Pool Resources and Fair Greenhouse Gas Emissions

Philosopher Megan Blomfield (2013) takes *the tragedy of the commons* and uses it to discuss several ways in which we could deal with these seemingly unsolvable problems. What we can see in Blomfield's (2013) work, is the use of a GT framework to build towards a political and ethical exploration of the climate crisis. Blomfield uses the framework of Common Pool Resources (CPR) where the amount of greenhouse gasses we can emit is finite and every large geopolitical actor can contribute to it as they see fit. Blomfield then discusses the consequences of dividing this equally around every human of earth's population. Difficulties arise when we start considering unequal division of resources and so-called carbon sinks (parts of land that are especially important for the atmosphere's stability).

Textbox 17

The Decision-Makers

In Chapter 1, large organizations and nations were defined as likely players in a quantum network. Blomfield (2013) takes a similar approach. For her, the actors being represented in a GT-like system are not individuals, but governing bodies (specifically nation-states or land-owning groups). These bodies are taken as *actors that decide how much emissions they want to make*. This is also the type of actor we are looking to make. The QN case concerns decision-making bodies instead of decision-making individuals.

It would be possible to specify these bodies to a specific set of organizational bodies, such as governments, hospitals, or companies. As with other large computational facilities, however, it makes sense that multiple bodies make use of the system at the same time. This is already the case with computational services such as High-Performance Computing. If a specific institute or a nation, decides to invest in QN, we assume that they are interested in exploring all different applications. This makes specification to one group unnecessary, and the case instead assumes an unspecified government-like body.

The Game

The baseline of the game (or system) is visualized as Figure 6 and Figure 7.

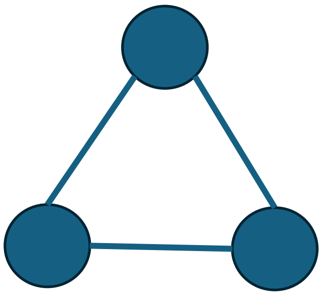


Figure 7: Libertarian Scenario (Scenario 1)

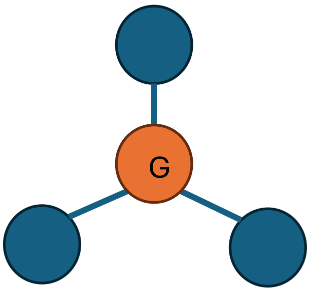
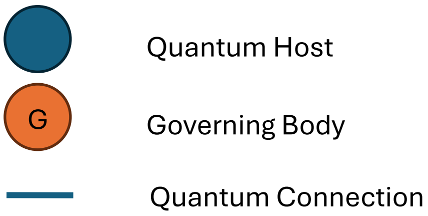


Figure 6: Governed Scenario (Scenario 2)



The difference between these two scenarios is that the first assumes a fully blind connection between the actors. Within this blind connection, actors are unaware of how others are using the system. This allows each actor to use the system in whatever way they see fit. This scenario is referred to as the *libertarian scenario* from now on.

The second scenario has a governing body that oversees the transmitted data. This would allow the actors to put together rules and regulations for what the connection and shared computation can be used for. In this scenario, the actors enter a secure connection with the governing body from which the governing body can then transmit the information to the other two actors. This scenario is inherently less autonomous and requires the maintenance of a central governing body. Because the governing body can still establish blind connections with the other computational systems, the other hosts are still unable to decipher the specific informational contents, but the governing body can verify whether the system is used properly. This scenario is referred to as the *governed scenario* from now on.

The reason for exploring both scenarios 1 and 2 is that both capture an important aspect of a future quantum internet. The first scenario is fully aimed at exploring the capabilities of a blind computation network. This a novel application of QT, and therefore an exploration of this specific capability is interesting. A full-blind connection does allow for easy exploitation. Because it is highly unlikely that large competing actors will give unconditional access to such a vulnerable technology, Scenario 2 is more realistic, and therefore worth exploring.

Section 4 of Chapter 1 already discussed some of the interactions and the decisions that actors can make in the case study. One of the important aspects was the dual-use nature of QT. For the case study, the actors can decide to act on their connection in several ways:

- Use the system in a fair/ethical way (medicine, optimization, etc.)
- Use the system in a notorious way (encryption breaking, military applications)
- Discontinue the connection with one specific actor or with the entire system.

Game Mechanics.

Depending on how each actor decides to use the system, other actors get a chance to reevaluate their decisions. This means that, if one of the actors decides to use the system maliciously, the others can decide to disconnect them from the system. These scenarios play out differently based on which of the two systems is in place.

While it would be possible to do a full (computational) simulation of this system, I decided to evaluate them by logically thinking through the scenarios and writing out their outcomes. The results talk through the different outcomes instead of writing them out in formal logic. This decision has been made to make the exploration readable and graspable for nontechnical readers and to set the scenarios up for discussion and elaboration. This approach is possible because, in a 3-actor system, the number of outcomes is still limited. Depending on the attitude of the actors, most of these scenarios eventually reach an equilibrium state.

The dual-use nature of QN is explored as follows. Each of the actors is given a starting condition where they want to either (1) make use of the system in a way that is constructive for all, or (2) use the system in a way that could be destructive for the other actors. This determines their starting behavior. After this, each actor strives to optimize their personal situation.

Defining Utility

Which scenario an actor works towards is based on their perceived utility. In GT, there is no singular way of defining utility. One important aspect of defining utility is differentiating between ordinal and cardinal definitions. For the ordinal definition of utility, only the position of the outcome (1st, 2nd 3rd, etc.) matters (Ross, 2024). This means that there is no difference in whether utility increases by 1 or by 99. Consider the bundles described in the formulas below. For an ordinal function, it would not matter whether the bundles are defined in the left or the right way. This is contrary to, what is known as a cardinal function, where moving from a to b would be severely more impactful for the right division (Ross, 2024). For a cardinal, the numerical difference between the options does matter.

$$Outcome\ a = 3 \qquad Outcome\ a = 9999$$

$$Outcome\ b = 2 \qquad Outcome\ b = 10$$

$$Outcome\ c = 1 \qquad Outcome\ c = 1$$

The case assumes that each actor tries to optimize their available computational power in a cardinal manner. This means that having the computational power of 3 actors is three times as desirable than having only one's computational power.[11] For other aspects than computational power quantifying is less desirable. This is because some advantages of a quantum system are not concerned with the quantity of computational power. One example of this is the ability to make use of a QKD system. Whether a QKD system can be implemented depends on the availability of a network connection and not the amount of computational value. Apart from a yes or no, there is no quantifiable value that can be attached to such a quality.

Therefore, it makes sense to do the overall evaluation in an ordinal fashion, where more computational power with the same capabilities and autonomy is desirable. The following aspects are considered as relevant.

1. Higher computational power
    - Computational power for three actors is three times as desirable.
2. Autonomy in using this computational power.
    - Using the system in a notorious way (and getting away with it) results in more benefits for an actor because they do not need to conform to regulations.
    - This includes less utility for a scenario where the actors must maintain a regulatory body since maintaining these is a time- and resource-consuming process.
3. Regular benefits from being part of the system.
    - Advantages from entanglement distribution.

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[11] There are more things to consider here than just linear scaling.
Actors could, for example, be in a spot where quantum advantage is not reached yet. Being below quantum advantage, the point at which a quantum computer can outperform a classical computer, would mean that any quantum computation is redundant compared to classical computation. Increase in computation would, besides researching the computer itself, only benefit if one has achieved this quantum advantage. On the other hand, there could also be a point where increases in computational power only marginally impact the improved performance of the system.
Currently there is little know about the specific computational costs of certain applications. Therefore, I will stick with the linear dependency as it (1) does not overcomplicate the model, and (2) still represents the costs and resources required to host these systems.

- being able to secure communication through QKD.

This means that the possible outcomes of the scenario are as follows (In order of desirability).

1. Full computational power with full autonomy (most desirable)
2. Full computational power with less autonomy
3. Less computational power with full autonomy
4. Less computational power with less autonomy
5. Disconnected without the benefits (least desirable)

If a specific scenario reaches an equilibrium (a state where none of the actors desires any change in their connection) the game stops. Scenarios without a clear equilibrium are discussed further for possible resolutions.

Closing of the Chapter

This chapter was concerned with what it means to **be guided by the field of game theory**. The aim was to construct a GT-inspired methodology to study the QN case from Chapter 1. By evaluating the field of GT and working through examples, the chapter distinguished between different applications of GT models. The difference between normative and descriptive models received strong attention. The end product was a GT-inspired methodology for studying different outcome scenarios in the quantum case.

What it means to **be guided by the field of game theory** is in this case not a formal GT approach. The final methodology did incorporate different aspects of GT, such as utility and equilibrium. Even though these concepts come from the field of GT, the methodology was unlike formal (or mathematical) GT and can be better described as GT-inspired. One could consider this a weakness because the results exist more *adjacent to* than *fully within* academic GT.

For the context of this thesis, however, it makes sense to stick with a GT-inspired approach over a formal GT. In the current GT-inspired approach the results are much less driven by calculation/modeling than if they were formally modeled. Instead, the results are talked through in a more discursive manner. This fits the form of the thesis, which is also more narrative and discursive than mathematical.

Now that all the discussion of QT and GT has been done, Chapter 3 can start by answering the question “What lessons can game theory teach us about quantum networks?”

Chapter 3: Lessons from the Game-Theoretic Approach.

Opening of the Chapter

This chapter is the culmination of all the technological setup of Chapter 1 and the methodological setup from Chapter 2. Because of the synergetic nature of this third chapter, allow me to briefly reflect on what has been done thus far.

The thesis aims to see how GT can help in understanding the future of QT, with a specific focus on QN. The first Chapter focused on exploring the technology behind and the capabilities of QN. From this chapter, a case containing actors, decision options, and interaction possibilities was constructed. Chapter 2 discussed GT as a modeling approach and described in what way GT can help us in this technological assessment. This was done by exploring what it means to model with a GT approach. From this, a specific GT-inspired setup for studying a future quantum network was built. This chapter details the results of this setup.

The first section details all the outcome scenarios that are possible from the game constructed in Chapter 2. From these outcomes, two specific lessons for hosting a future quantum network are written out. These lessons and the methodology itself are then discussed in the final section of this chapter, along with suggestions for future improvement.

S1 The Outcomes

The previous section described two different scenarios: the first without a governing body (Libertarian Scenario) and the second with a governing body (Governed Scenario). The different outcomes of these cases are discussed in that order. The different outcomes in each scenario are presented in a didactical order, meaning that the earlier outcomes are intuitive and require only a few logical steps, and can help create understanding for the latter, more complex ones.

The outcomes are discussed with full commitment to the outlines of the case study. Therefore, some outcomes might be less realistic in the current political landscape. This is because, within this framework, there is no way of ranking different outcomes on probability. Therefore, the purpose of exploring these different scenarios is to find recommendations that promote desirable outcomes while limiting undesirable ones. After laying out every possible outcome scenario, we can examine what rules and regulations would be suitable to prevent unwanted outcomes and promote the desirable ones.

To explore the dual use of QN, each case is played out in the assumption that actors behave benevolently (B) or attempt maleficence (M). In all scenarios, the behavior of all actors is summarized as (#B, #M) which equates to (Number actors behaving benevolent, Number of actors behaving maleficent).

Overview and Evaluation Criteria

Table 2 features an overview of all outcome scenarios to be discussed. All outcomes are evaluated on specific criteria. The criteria are inspired by the 5 criteria used by Possati & Vermaas (Forthcoming). In their case study, they used the following five criteria to evaluate different scenarios: Practical quantum advantage, Collaboration gain, Equality, Transparency, and Autonomy. Because there are some differences between their study and this thesis, it makes sense to change the parameters somewhat.

For one, transparency and autonomy are already baked in the different scenarios. All libertarian cases have full autonomy and no transparency. The governed cases have transparency and less autonomy. Therefore, evaluating these criteria is of little use. Others, like collaborative gain and practical quantum advantage, can be combined into a simpler loss of computational power. This is because, in the GT case study, we have not defined specific quantities for getting to a quantum advantage. Instead, we assumed all actors desire to increase their computational power as much as possible.

There are also some uncertainties to be resolved, such as the tension in scenario G2 where the responses of different actors do not reach a clear equilibrium. These uncertainties are noted in the overview table *(Table 1)* and further discussed in the second section.

Scenario	**(#B, #M)**	**Equal benefit across actors?**	**Outcome**	**Loss of computational power?**	**Equilibrium reached?**
L1: Benevolence	(3B, 0M)	Equal	Connected system	No	Yes
L2: Full Maleficence	(0B, 3M)	Equal	Connected system	No	Yes
L3: Unfair Advantage	(1B, 2M) or (2B, 1M)	Unequal	Connected system	No	Yes
G1: Governed Safe	(3B, 0M)	Equal	Connected system (with governance)	No	Yes
G2: Governed Compromised	(2B, 1M)	Unequal	Partially connected system *OR* fully connected system*	Possibly	No
G3: Unwanted Alliance	(1B, 2M)	Unequal	Partially connected system *OR* fully connected system**	Possibly	No
*Depends on the behavior of 1M **Depends on the behavior of 1B					

Table 1: Overview of all outcome scenarios

Most of the scenarios feature additional happenings that cannot be fully detailed in the overview table. Therefore, each of the scenarios is discussed in more depth.

Libertarian Scenario

The libertarian case has the benefit that outcomes are easily determined. This is because the Libertarian Scenario assumes a fully blind connection between the actors. This means that actors have no awareness of each other's decisions on how to use the distributed computing power. Because they have no extra information about the other parties, it makes little sense that actors would change their behavior in the system after their initial decision. Therefore, all initial situations are also outcome situations.

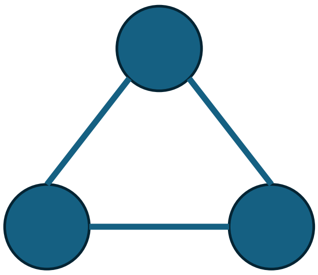

Figure 8: Libertarian Scenario

There could be external reasons for an actor to change whether they would want to stay connected or not. Currently, there is no mechanism in the case study to simulate such behavior. Therefore, it is assumed that the actors do not communicate their intentions and actions to the other actors. These scenarios also assume that there is no way for actors to discover how they are using the systems. Of course, there are ways to discover this outside of the computational network itself (intelligence agencies, whistleblowers, or other human means). These aspects, along with other shortcomings of the method, are discussed at the end of this chapter.

Scenario L1: Benevolence (3B, 0M)

This outcome seems the most desirable and fruitful. In this outcome, all actors decide to use the system in a *benevolent* manner. They use the distributed computing of the system in a way that does not go against the desires of the other actors. Each actor retains full autonomy with no risk of sensitive information being taken by the other actors (blind connection). In this outcome, each actor benefits equally from the collaboration.

This scenario would see benefits for all actors equally. Using computation for advancing medicine or computer optimization can be of benefit to all. Simulations in clinical and medicine, for example, could be conducted in a faster manner for all (Flöther, 2023). This holds for all other fields that benefit from the advantages of quantum systems.

Scenario L2: Full maleficence (0B, 3M)

This scenario is in many ways like outcome 1, except that actors use the system for selfish or maleficent ends. This means that the actors still benefit from each other's computational power, but the outcomes of these computations are self-serving. This means full autonomy for all actors, but also the possibility for destructive applications. Such applications can result in harm. Examples include military developments or intelligence gathering through decrypting information.

In general, this outcome is undesirable for all actors. Because all actors are acting in self-interest, there is no mutual benefit from their computations. The benefit one actor receives from gathering intelligence and military developments equates to the same amount of harm through others using the system against them. While undesirable, this outcome could still be considered *fair*. This is because all actors have the same advantages and disadvantages.[12]

Scenario L3: Unfair Advantage (1B, 2M) or (2B, 1M)

This scenario sees one or two actor(s) using the systems for benevolent means while the other(s) use it for maleficent means. The actors who decide to use the system in a benevolent way benefit from the computational power for their ends. The actors deciding to use the system in a maleficent way benefit by being able to decrypt intelligence on the others and build a military arsenal. While both provide respective advantages, the maleficent applications could be destructive for the benevolent actors.

The actors deciding to use the system in a benevolent way have no way of knowing that the others are using it in a maleficent way (and vice versa). This is because of the blind connection and no governing body. Again, there could be ways in which they figure this out and retaliate through other means (through human failure for example), but such happenings are not incorporated in the case study. Therefore, this is discussed later. For now, this means that there is no way of retaliating against potential abuse of the system.

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[12] This fairness does not hold when considering actors outside of the quantum network. They do not have the advantages of these three actors, but can still be harmed by their actions.

Governed Scenario

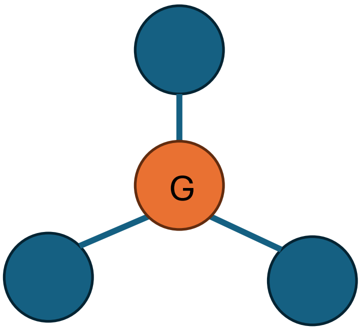

Figure 9: Governed Scenario

The governed scenario has a more complicated set of outcomes. In this scenario, the actors have agreed to, instead of connecting to each other, first connect to a governing body. This means that each actor has a blind connection to the governing body and the governing body can distribute computational processes between the different actors. In this case, actors can still make use of distributed computing but have a governing body in place that can regulate agreements between the three. In this case, the government body would be able to take notice of potential misuse, meaning that malicious use of the system does not go without notice.

Scenario G1: Governed Safe (3B)

This first outcome is similar to L1. All actors keep their end of the agreement and therefore can make use of the system in ways that contribute to overall wellbeing. The advantages are alike, and the benefit division is fair.

Where the benefit/utility would differ from L1 is that certain advantages of the quantum communication system would be lost. These include an added point of sensitivity. The governing body acts as a central hub for all computations. Having an extra hub in the system means added vulnerability. This vulnerability could be physical because the computational network needs to be built with this added actor in mind, but also governmental. Failure to organize the governmental body well can result in potential misuse and corruption. Even if the government body works perfectly, all actors have to face the increased costs of maintaining a secure and functioning governing body.

Scenario G2: Governed Compromised (2B, 1M)

Scenario G2 is the first scenario that does not reach an immediate equilibrium. If one actor decides to go against the mutual agreements and use the system in undesirable ways, the others must decide how they wish to respond. Removing the misbehaving actor from the computational network results in less computational power for themselves since the system retains only 2/3rd of its total computational power. Letting them stay and keep misbehaving means the possibility of further abuse from the system but allows for all actors to keep using the computational power. There are different ways in which these actors can respond (Table 2).

Action	**Description**	**Outcome**
Permanent punishment (Trigger)	The remaining two actors permanently exclude the misbehaving actor from the system.	The remaining actors lose 1/3rd of their shared computational power. The misbehaving actor permanently loses 2/3rd.
Temporary Punishment (tit-for-tat)	The remaining two actors punish the misbehaving actors by removing them temporarily from the system.	Same as above, but temporarily. Changes depend on whether the malicious actor decides to cooperate in the future.
Let Be (unconditional collaborate)	The remaining actors do not act upon the misbehavior and leave the third actor in the system	All actors retain computational power. Misbehavior is not acted upon.

Table 2: Retaliation Strategies Against Misbehavior[13]

Each of these scenarios has its own merits. Both *Temporary Punishment* and *Let Be* allow the two remaining actors to retain the full computational power. Such an increase could, for example, push them over the edge of quantum advantage. Both could also be seen as soft modes of governing because they allow the third party to exploit their computational power for selfish reasons. Permanent exclusion from the system could therein be seen as a strong *zero-tolerance* mode of governance. This would, however, also see them permanently lose computational power. Because of these different options, there is no immediate solution or outcome for this specific scenario.[14]

Scenario G3: Unwanted Alliance (1B, 2M)

While punishing intuitively happens against misbehavior, this case study allows for miscellaneous actors to span together against benevolent actors. If two parties decide that they want to use the system without any regulation, they could decide to overrule the single actor. If we assume the governing body to be corruptible, then we can get such an unwanted alliance.

The opposing (benevolent) actor herein has three opportunities. (1) Disconnect from the system to take away some computation from the others. (2) Stay within the system and still use it for benevolent means. (3) Confirm to miscellaneous behavior. Similar to G2, this scenario does not reach an immediate equilibrium.[15]

Left out scenarios.

The governed case could have one more scenario where all actors decide to behave maleficent. This scenario was left out because it would be unlikely that these actors would set up a governing body in the first place.

I decided to leave out possible outcomes where actors decide never to connect to the system in the first place. The benefit of using GT as a method is that it allows for exploring interactions between actors. If actors immediately decide not to connect, there are no interactions and therefore no reasons to study them.

Other considerations

It should be noted that, if all players have access to QN, they could be making use of post-quantum or QKD encryption. This would make the data resistant to decryption by a quantum computer. Therefore, malicious use through intelligence gathering would become impossible.

Overcoming encryption cracking through post-quantum encryption or QKD, however, does not protect against all cases of malicious use of quantum computation. There are, for instance, concerns about *Save Now, decrypt later* strategies, which was mentioned earlier in Chapter 1 in the section on quantum cyrptography.. One could also consider military applications, as discussed in Chapter 1, here. These examples show that, even if all decryption practices can be

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[13] This list of strategical responses is adapted from (*Prisoner's Dilemma > Strategies for the Iterated Prisoner's Dilemma (Stanford Encyclopedia of Philosophy),* n.d.). The orgin of these strategies will be discussed in the second section of this chapter.

[14] The second recommendation of Section 2 will explore this specific tension further.

[15] This tension will also be explored in recommendation 2 from section 2.

prevented with quantum-proof encryption, there is still the possibility of using the system in other miscellaneous ways.

S2 Two Lessons from the Case Study

There are some lessons we can learn from all these outcomes. These lessons are described here as two recommendations for governing a future quantum internet. These recommendations aim to (1) prevent malicious usage while (2) not interfering with desired outcomes. For QN, this means pursuing scenarios where more actors share their computational power while preventing as much malicious use as possible.

The first recommendation is about the value of redundancy in QN, which applies to all scenarios. The second recommendation deals with retaliation strategies and therein concerns the tension in scenario G2 specifically.

Lesson 1: The Value of Redundancy

QN could benefit from an increase in participating actors. There are two reasons for this.

First, in the current 3-actor scenario, losing one participant significantly impacts the others. Losing a third of their computational power means a significant decrease in the usability of their system. If the system, however, were to consist of more than three actors, this loss would not make up such a large fraction of the system. Quantitatively they could still lose the same amount of computational power, but percentage-wise, it is less impactful.

Second, any actor attempting to use the system maliciously would suffer more greatly from being disconnected from the system. Being disconnected from a larger system means a larger decrease in computational power. If we consider all actors to behave in their interest, betraying others means a larger punishment for them. This would make misbehavior less likely.

This recommendation translates well to many other shared resources take place outside of the QN case, they especially hold value for QN. This is because the applications of quantum computers only make sense when the computer has sufficient computational power. Quantum computers can outperform classical computers in specific domains, but only when they are large enough (quantum advantage). If the owner of a quantum system is below this tipping point, there is no benefit to their quantum computations compared to classical computing systems. Therefore, whether an actor is or is not at this point of quantum advantage matters significantly. Redundancy can ensure that all collaborating actors do not tip below this point and give misbehaving actors a reason to do better.

A requirement for harnessing the benefits of a system that allows for redundancy is the construction of the physical network. The benefits of redundancy are most fruitful in scenarios where all actors have intertwined connections. In the three actors case discussed here, all actors relate to each other. Figures 3 and 4 show examples of a 9-actor network where, in Figure 3, one central actor is vital for the others' connectivity, while, in Figure 4, each actor can be missed. The benefits of redundancy, therefore, depends on the physical network infrastructure.

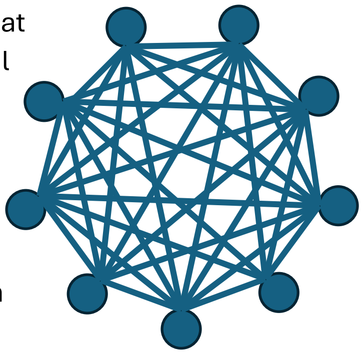


Figure 10: Rigid 9-actor network.

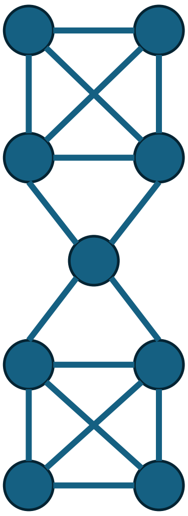


Figure 11: vulnerable 9-actor network.

Lesson 2: Governance Strategy

Scenario G2 sees different ways in which actors can retaliate against misbehavior. Literature on GT can help us in navigating this tension. Specifically, the work done in the iterated prisoner's dilemma. The iterated prisoner's dilemma (Textbox 18) has been used to explain how collaboration can emerge from competitive scenarios. Its outcomes relate to our QN case study in the following way.

Like the *regular* prisoner's dilemma, a player in the iterated prisoner's dilemma can decide to pursue collaboration or choose to exploit the other player. When playing the iterated prisoner's dilemma, one must consider an opponent's behavior over a prolonged time. Betraying in the first round may result in a better initial reward but could be destructive to one's results over time. The iterated prisoner's dilemma also requires actors to think about how they would respond to opponents possibly betraying them. Forgiveness might lend itself well to exploitation, but harsh punishment removes any possibility for future collaboration.

Around the 1980's, researcher Robert Axelrod (2006) organized a tournament version of the iterated prisoner's dilemma. In the tournament, different strategies were pitted against each other. The tournament aimed to see how different strategies would fare against each other over a longer period and against a multitude of opponents. Axelrod's findings were therefore not about the *best* strategy in any particular matchup, but instead about which strategies would be resilient in the long run.

Textbox 3.1: The iterated Prisoner's dilemma

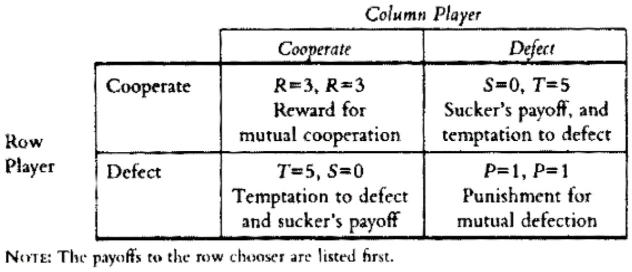
The iterated prisoner's dilemma is a tournament version from the prisoner's dilemma as described before. A multitude of actors play against each other in repeated games. Because they play against each other multiple times, they can integrate knowledge about the previous happenings to change their strategy for the next rounds. If one's main strategy is seeking cooperation, but their opponent keeps betraying, they can choose to change their behavior to match the opponent.

The tournament sees all actors playing against each other for several times. After a multitude of games the worst performing strategies are eliminated and replaced by copies of the winning strategies.

The basic payoff structure for the iterated prisoners dilemma is taken as in Figure 12 (Axelrod, 2006).

Textbox 18

The outcomes of Axelrod's (2006) tournament are relevant to the quantum case study. The tension in the iterated prisoner's dilemma, between short-term self-serving gain and long-term collaborative gain is exactly the tensions faced in scenario G2. In G2, one player has decided to work against the other player's interests and pursue self-interest. The other actors can decide to retaliate harshly or retaliate in a forgiving manner. The outcomes from Axelrod's tournament give us insight into how different retaliations play out.



		Column Player	
		Cooperate	Defect
Row Player	Cooperate	$R=3$, $R=3$ Reward for mutual cooperation	$S=0$, $T=5$ Sucker's payoff, and temptation to defect
	Defect	$T=5$, $S=0$ Temptation to defect and sucker's payoff	$P=1$, $P=1$ Punishment for mutual defection

NOTE: The payoffs to the row chooser are listed first.

Figure 12: Payoff diagram from Axelrod (2006)

Option 1: Trigger (FRIEDMAN)

The first retaliation strategy detailed in Table 2 was a TRIGGER strategy. In this strategy, any misstep from a player would result in a permanent disconnect from the system. The outcome would see the remaining players suffering a small loss in their computational power, while the punished player would lose significantly more. Such a *zero-tolerance policy* seems like a strong mode of governance, but within GT, it is considered less beneficial.

In Axelrod's tournament, this *zero-tolerance* strategy was called the FRIEDMAN strategy (Axelrod, 2006, p. 36). The FRIEDMAN strategy benefits from indefinite cooperation and retaliates strongly against all others. What the strategy did not allow for, however, was for players to redeem themselves. Some strategies in the tournament would occasionally defect to test whether they were able to exploit their opponent. FRIEDMAN would lock these players out of collaboration for the indefinite future. By responding in such a harsh manner, actors remove the option for the misbehaving actor to redeem themselves. In Axelrod's tournament, FRIEDMAN was one of the lowest-scoring strategies (Axelrod, 2006, p. 36).

Option 2: Let Be (ALWAYS COOPERATE)

The strategy of *letting be* was successful in scenarios where collaboration was the standard but would be easily exploited. In Axelrod's tournament, a strategy such as this one would be easily exploited by strategies that tested whether an opponent would collaborate indefinitely (such as the "TESTER and TRANQUILIZER" strategies (Axelrod, 2006, p. 44)). While always collaborating is certainly a noble strategy, it allows for easy exploitation and is therefore quite vulnerable.

Option 3: Punish (TIT FOR TAT)

One of the most successful strategies in Axelrod's (2006) tournament was the TIT FOR TAT strategy (Axelrod, 2006). The TIT FOR TAT strategy would start with collaborating and would then copy the opponent's last decision. Contrary to TRIGGER, TIT FOR TAT uses a temporary retaliation. Therefore, strategies that would test the water, such as TESTER and TRANQUILIZER, would quickly return to collaboration. TIT FOR TAT would then follow this return to collaboration. Axelrod (2006) himself attributes the success of this strategy to the following four aspects. (1) It remains benevolent when others are too, (2) it retaliates, meaning that it does not allow for easy exploitation, (3) it is forgiving, meaning that it allows to return to a state of full cooperation, and (4) it is a clear and simple strategy (Axelrod, 2006, p. 20).

Axelrod's (2006) findings on the TIT FOR TAT strategy translate well to the QN case. Scenario G2 requires the two remaining actors to decide in what way they wish to retaliate against the third opponent. The specific outcomes are slightly different, but overall, the favourability of their different options remains similar. We can stick with Axelrod's (2006) explanation for the success of TIT FOR TAT to see how it fares well in the quantum scenario. (1) The strategy allows for retaining collaboration with other collaborative actors, (2) the strategy retaliates against exploitation, (3) it allows for the return of the missing 1/3rd of computational power and (4) the simplicity of the strategy allows other actors to know what they are dealing with. Aiming for cooperation and retaliating against misbehavior when needed, but retaining a forgiving attitude, therefore seems to be the most valuable strategy to overcome the problems of scenario G2.

Another benefit of temporary punishment is that it allows for dealing with false positives. Thus far, the governed scenario has assumed that all malicious behavior is fully detectable, but it is not unthinkable that such detection can go wrong. In the permanent-ban strategy, a false positive would result in an actor being removed from the system and an overall decrease in the system's computational power. The forgiving nature of the temporary ban strategy allows for overcoming false positives and returning to a fully cooperative scenario. In the iterated prisoner's dilemma, this has been discussed in the context of *dealing with noise* (Wu & Axelrod, 1995), where actors sometimes 'accidentally' act differently from their intention. Permanent punishment strategies would suffer from such accidents, while temporary punishment can overcome these negative effects over time.

S3 Discussion of the Methods.

The two recommendations discussed above follow from the outcomes of the case study. Before bringing these recommendations to a conclusion, there are some aspects of the method that require evaluation. This discussion of the method features, (1) disadvantages and limitations of the method, and (2) possibilities for improvement.

Disadvantages of the Method

No predictive power

In this thesis, it was determined beforehand whether an actor would show benevolent or maleficent behavior. This allowed an exploration of all possible outcomes, but not a prediction of which outcomes are more likely. In its current state, the case study holds no predictive power, and each scenario is considered equally likely. The recommendation contributed by fitting all possible outcomes. This provided suitable results but could be considered a *brute-force* approach to the problem. This *brute force* approach is only possible because of the simplicity of the case (3 actors) and would become less viable if we were to include more actors/parameters in the case.

Whether these predictive aspects are desirable and possible remains to be seen. The possibility for a predictive model is discussed shortly in the *points of improvement* section.

Impact on actors outside of the case

An important question for the future of QN is whether the benefits of the technology are accessible in an equal and fair manner. The different scenarios in Table 2 explore this somewhat by detailing whether the computational resources are equally divided among all participating actors. This could be seen as an evaluation of whether the benefits of the technology are distributed fairly. What the evaluation excludes, however, is a consideration of actors not involved in the system. Some of the scenarios described in Table 2, see an equal division between actors, but in the real world, this consideration should also include whether the technology and its benefits are accessible to all. Concerns about the accessibility of the technology are being explored in other literature already (De Jong, 2022; De Wolf, 2017; Kop et al., 2023), and should receive further attention as the technology becomes more mature.

Other aspects

The case study, as with all models, cannot be equated with reality itself. There are infinite ways in which actors could subvert the decisions given to them in the case study. We have assumed, for example, that network connections can only be disconnected from an active decision from all actors. In reality, these systems are vulnerable to all sorts of attacks. The physical infrastructure discussed in Chapter 1, can fail, or be intentionally destroyed. The specific model built here works well for studying the interaction between decision-makers but does not allow for describing other political processes such as corruption, monetary cost/gain, and the current geopolitical tension between nations.

Another important consideration is that, while a quantum system is informationally secure, there are other ways in which actors could figure out what specific details are communicated (such as through human failure). Integrating all these things would mean making a 1:1 representation of reality which is (likely) impossible and (definitely) outside of the scope of this thesis.

Points of Improvement.

Possibility for a predictive model

In Chapter 2, Section 3 the decision was made to pursue a normative model instead of a descriptive model. If the model were to take a more descriptive approach, it could be possible to evaluate outcomes on likelihood. Within GT, there are examples of such predictive models in applications of network security and peer-to-peer energy trading (Chen & Zhu, 2018; Farhang et al., 2014; Tushar et al., 2019).

Tweaking this thesis' normative model into a descriptive model (or a model with descriptive components) would require changes. GT, as used in this thesis, assumes that actors strive to optimize their own expected utility. Whether this accurately represents the way that organizations make decisions is questionable.

One critique against this assumption of rationality is that "people frequently act in ways deemed to be irrational by decision theorists" (Peterson, 2017, p. 311). One such example is that "people tend to overestimate small probabilities, but underestimate moderate and large probabilities" (Peterson, 2017, p. 315). Incorporating these biases would make the model more complex, but they have shown themselves to be more accurate in predicting decision-making in simple scenarios.

One field to describe these departures from expected utility theory is the field of prospect theory. Prospect theory refocuses utility on "gains and losses rather than final assets" (Kahneman & Tversky, 1979, p. 263). Prosect theory features the over- and underestimations from the previous paragraph among other departures from utility optimization. Incorporating these tendencies would require shifting utility away from optimizing for the total amount of computational power.

Whether these theories are immediately applicable to the QN case remains to be seen. Most of these decision-making theories, such as prospect theory, have been empirically tested with individual decision-making. The QN case described in this thesis deals with larger institutional bodies. Whether these fields two translate well is not fully known. There are fields of decision-making that are concerned with organizational decision-making processes (Galavotti, 2019), but these theories are more concerned with processes of information management and the specific roles in an institution. Applying decision-making theories of individuals to institutional decision-making would require an in-depth understanding of the institutes that are represented in the model and their decision-making practices. Whether such fields can provide us with grounded predictions remains to be seen.

Scaling the model

Another possibility for improvement is to scale the model for more than three actors. The consequences of this have been somewhat explored through the recommendation about redundancy.

Extra complexity can be added by involving players who do not have computational power but can still make use of the system. These actors could receive other means of collecting/sending quantum information (such as through a quantum sensor). This could also include a specific exploration of safety in these networks. Especially the inclusion of non-quantum repeaters,[16] as discussed in Chapter 1, would provide an interesting exploration of security. This is because non-quantum repeaters add extra points of vulnerability in these systems.

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[16] Specifically section 3

Conclusion and Meta-Reflection

This thesis aimed to explore quantum network technologies using GT as an analytical approach. Overall, this aim has been achieved. Important aspects of QN, such as blind and distributed computing, were integrated in a future scenario. This scenario was then molded by insights from the field of GT into a specific methodology. The result of this methodology was an overview of all outcome scenarios. GT herein showed itself as a useful tool for turning complex network dynamics into a graspable and analyzable scenario.

The specific research question of the thesis was formulated as: **How can the development and governance of quantum networks be guided by the field of game theory?** The two lessons described in Chapter 3, about redundancy and the success of a retaliating but forgiving *TIT FOR TAT* strategy, emerged from the GT model and applied to QN. These lessons can inform the governance and development of QN.

Even though there is still room for specification, the lessons are concrete, graspable, and emerged quite naturally from the established GT method. These results speak of success in answering the main question. The answer to "**How can the development and governance of quantum networks be guided by the field of game theory?**" could therefore be formulated as: *By examining the possible outcomes of collaboration in a GT-inspired QN case study. The lessons here are that: in developing QN technology, we should aim for the participation of many actors and have this collaboration be cooperative and retaliating when needed.*

These lessons could be translated into concrete policy recommendations. This would, however, require more knowledge of governing network systems and up-to-date knowledge of governance around quantum systems. Because this thesis has not done any of these things, the next best thing is to give more abstract aims for policy development.

Achieving redundancy in QN would require making sure that multiple organizations have access to the resources required to develop these technologies. Therefore, collaborating and sharing information through open science is a valuable practice, since it would lower the knowledge threshold to participate in a shared network.

The lesson on strategy can be used as an argument for collaborating. The lesson shows that both unconditional collaboration and harsh punishment are not valuable in the long term. This lesson is less useful for rigid policy recommendations, and whether it is taken to heart depends on the kind of governing bodies in place. A governing party with a strong focus on sovereignty, for example, might push away the argument even if it means less benefit. Although the lesson quite clearly lays out the advantages of a forgiving but retaliating strategy, the possibilities for concrete policy here are few.[17]

There are some comments to make w.r.t. the usefulness of the approach. One important consideration is whether there is more useful knowledge to be gained from the use of GT for studying the dynamics in emerging technologies such as QN. The specifics of the (iterated)

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[17] I consider policy here somewhat as "this is written on page" and strategy as something that has to be discussed and evaluated over time. Constructing a policy on open science seems more attainable than constructing a policy on forgiveness, especially when it is about collaboration between large organisations. Of course, policy can inform and even determine strategy for a longer period, but I deemed policy and strategy separate enough to distance the strategy recommendation from its usefulness for policy.

prisoner's dilemma and the findings from Axelrod's (2006) tournament were particularly useful for this specific case. Whether the entire field of GT always lends itself to such explorations remains to be seen.

Further exploration with GT in QT is possible. What should be noted, however, is that the argument made in this thesis is particular and does not allow for immediate upscaling. Modeling all developments in an emerging field such as quantum is difficult. There are a lot of extra considerations that need to be made, such as geopolitical tensions, failure in governmental decision-making, fairness w.r.t. non-quantum participants, cultural differences, and uncertainty in the development of quantum systems. The suggestions from the previous chapter on further developing the model for predictive capacity require a thorough consideration of cognitive decision-making. Do the assumptions in the model still match their real-world equivalent in organizational bodies?

While this thesis is not a definitive argument for GT as a method for studying QN, it can be considered an argument in favor of this approach. The outcomes naturally emerged from the exploration and were well-informed by the methods. This means that the combination of the two fields was productive. The lessons about redundancy and arguments for collaboration could have been argued from other fields. What GT contributed here was an analytical red thread and a history of previous research into the topic of collaboration. GT could therein be considered the analytical glue to lay out a healthy argument.

There is no singular prediction tool that helps to bring about a fair and desirable future for QT. This thesis stuck with one particular focus, but there are many other methods of assessing QT. One example is the inclusion of morality in the assessment of outcomes, such as approached by Possati and Vermaas (Forthcoming). Other methodologies in technology assessment, such as anticipatory ethics (De Jong, 2022) and Responsible Research and Innovation (Coenen & Grunwald, 2017) are examples of less rigid methodologies that can include wider societal consequences.

Some avenues have not been explored. One example is the examination of deliberative processes and the role they should play in the development of QN. Such processes are present in other technical fields already, such as ethical deliberation in software development (Gogoll et al., 2021). Exploring deliberation on QT could provide useful information from the social sciences, and would be especially interesting to quantum, as it still carries with it the complexity of metaphorical rocket science.

This examination has been one perspective. Let there be more to follow.

Bibliography

Awschalom, D., Berggren, K. K., Bernien, H., Bhave, S., Carr, L. D., Davids, P., Economou, S. E., Englund, D., Faraon, A., Fejer, M., Guha, S., Gustafsson, M. V., Hu, E., Jiang, L., Kim, J., Korzh, B., Kumar, P., Kwiat, P. G., Lončar, M., … Zhang, Z. (2021). Development of Quantum Interconnects (QuICs) for Next-Generation Information Technologies. *PRX Quantum*, *2*(1), 017002. https://doi.org/10.1103/PRXQuantum.2.017002

Axelrod, R. M. (2006). Chapter 1: The Problem of Cooperation + Chapter 2: The Success of TIT FOR TAT in Computer Tournaments. In *The evolution of cooperation* (Rev. ed, pp. 3–53). Basic Books.

Barad, K. M. (2007). *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Duke University Press.

Barker, W. (2021). *MIGRATION TO POST-QUANTUM CRYPTOGRAPHY*.

Blomfield, M. (2013). Global Common Resources and the Just Distribution of Emission Shares*: JUST DISTRIBUTION OF EMISSION SHARES. *Journal of Political Philosophy*, *21*(3), Article 3. https://doi.org/10.1111/j.1467-9760.2012.00416.x

Bonau, S. (2017). A Case for Behavioural Game Theory. *Journal of Game Theory*, *6*(1), 7–14. https://doi.org/10.5923/j.jgt.20170601.02

Broadbent, A., Fitzsimons, J., & Kashefi, E. (2009). *Universal blind quantum computation*. 517–526. https://doi.org/10.1109/FOCS.2009.36

Capra, F. (1975). *The Tao of physics: An exploration of the parallels between modern physics and eastern mysticism*. Wildwood House.

Chen, J., & Zhu, Q. (2018). Security investment under cognitive constraints: A Gestalt Nash equilibrium approach. *2018 52nd Annual Conference on Information Sciences and Systems (CISS)*, 1–6. https://doi.org/10.1109/CISS.2018.8362263

Chou, P. B., Bandera, C., & Thomas, E. (2017). A behavioural game theory perspective on the collaboration between innovative and entrepreneurial firms. *International Journal of Work Innovation*, *2*(1), 6. https://doi.org/10.1504/IJWI.2017.080729

Coenen, C., Grinbaum, A., Grunwald, A., Milburn, C., & Vermaas, P. (2022). Quantum Technologies and Society: Towards a Different Spin. *NanoEthics*, *16*(1), 1–6. https://doi.org/10.1007/s11569-021-00409-4

Coenen, C., & Grunwald, A. (2017). Responsible research and innovation (RRI) in quantum technology. *Ethics and Information Technology*, *19*(4), 277–294. https://doi.org/10.1007/s10676-017-9432-6

De Jong, E. (2022). Own the Unknown: An Anticipatory Approach to Prepare Society for the Quantum Age. *Digital Society*, *1*(2), 15. https://doi.org/10.1007/s44206-022-00020-4

De Wolf, R. (2017). The potential impact of quantum computers on society. *Ethics and Information Technology*, *19*(4), 271–276. https://doi.org/10.1007/s10676-017-9439-z

Denchev, V. S., & Pandurangan, G. (2008). Distributed quantum computing: A new frontier in distributed systems or science fiction? *ACM SIGACT News*, *39*(3), 77–95. https://doi.org/10.1145/1412700.1412718

DiVincenzo, D. P. (2017). Scientists and citizens: Getting to quantum technologies. *Ethics and Information Technology*, *19*(4), 247–251. https://doi.org/10.1007/s10676-017-9435-3

Farhang, S., Manshaei, M. H., Esfahani, M. N., & Zhu, Q. (2014). A Dynamic Bayesian Security Game Framework for Strategic Defense Mechanism Design. In R. Poovendran & W. Saad (Eds.), *Decision and Game Theory for Security* (Vol. 8840, pp. 319–328). Springer International Publishing. https://doi.org/10.1007/978-3-319-12601-2_18

Feynman, R. P. (1960). There's plenty of room at the bottom. *Caltech Engineering and Science*, *23*(5), 22–36.

Flöther, F. F. (2023). The state of quantum computing applications in health and medicine. *Research Directions: Quantum Technologies*, *1*, e10. https://doi.org/10.1017/qut.2023.4

Galavotti, I. (2019). Strategic Decisions: Theoretical Foundations of Organizational Decision-Making. In I. Galavotti (Ed.), *Experience and Learning in Corporate Acquisitions: Theoretical Approaches, Research Themes and Implications* (pp. 1–39). Springer International Publishing. https://doi.org/10.1007/978-3-319-94980-2_1

Gasser, U., De Jong, E., & Kop, M. (2024). A call for responsible quantum technology. *Nature Physics*, *20*(4), 525–527. https://doi.org/10.1038/s41567-024-02462-8

Gogoll, J., Zuber, N., Kacianka, S., Greger, T., Pretschner, A., & Nida-Rümelin, J. (2021). Ethics in the Software Development Process: From Codes of Conduct to Ethical Deliberation. *Philosophy & Technology*, *34*(4), 1085–1108. https://doi.org/10.1007/s13347-021-00451-w

Griffiths, D. J., & Schroeter, D. F. (2018). *Introduction to quantum mechanics* (Third edition). Cambridge University Press. https://doi.org/10.1017/9781316995433

Grinbaum, A. (2017). Narratives of quantum theory in the age of quantum technologies. *Ethics and Information Technology*, *19*(4), 295–306. https://doi.org/10.1007/s10676-017-9424-6

Han, Z. (Ed.). (2012). *Game theory in wireless and communication networks: Theory, models, and applications*. Cambridge University Press.

Hoofnagle, C. J., & Garfinkel, S. (2021). *Law and policy for the quantum age*. Cambridge University Press.

Jyothi Ahuja, N., & Dutt, S. (2022). Implications of Quantum Science on Industry 4.0: Challenges and Opportunities. In A. Kumar, S. S. Gill, & A. Abraham (Eds.), *Quantum and Blockchain for Modern Computing Systems: Vision and Advancements* (Vol. 133, pp. 183–204). Springer International Publishing. https://doi.org/10.1007/978-3-031-04613-1_6

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, *47*(2), 263–292.

Karstens, B., Kool, L., & Hijstek, B. (2023). *Quantum Technology in Society*.

Kop, M., Aboy, M., De Jong, E., Gasser, U., Minssen, T., Cohen, I. G., Brongersma, M., Quintel, T., Floridi, L., & Laflamme, R. (2023). 10 Principles for Responsible Quantum Innovation. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4475556

McCarty, N. M., & Meirowitz, A. (2007). *Political game theory: An introduction* (1. publ). Cambridge University Press.

Morelli, M., Casagrande, M., & Forte, G. (2022). Decision Making: A Theoretical Review. *Integrative Psychological and Behavioral Science*, *56*(3), 609–629. https://doi.org/10.1007/s12124-021-09669-x

Nordstrom, J. F. (2020). Introduction to Game Theory. *Linfield College McMinnville, Creative Commons Publication*.

Osborne, M. J. (2004). *An introduction to game theory*. Oxford University Press.

Perrier, E. (2022). *Ethical Quantum Computing: A Roadmap* (arXiv:2102.00759). arXiv. http://arxiv.org/abs/2102.00759

Peterson, M. (2017). *An introduction to decision theory* (Second edition). Cambridge University Press.

Possati, L. M. (2023). Ethics of Quantum Computing: An Outline. *Philosophy & Technology*, *36*(3), 48. https://doi.org/10.1007/s13347-023-00651-6

Possati, L. M. (2024). Quantum Technologies: A Hermeneutic Technology Assessment Approach. *NanoEthics*, *18*(1), 2. https://doi.org/10.1007/s11569-023-00449-y

Possati, L. M., & Vermaas, P. (Forthcoming). *The rationality and morality of connecting quantum computers*.

Prisoner's Dilemma > Strategies for the Iterated Prisoner's Dilemma (Stanford Encyclopedia of Philosophy). (n.d.). Retrieved June 4, 2024, from https://plato.stanford.edu/entries/prisoner-dilemma/strategy-table.html

Regev, O. (2024). *An Efficient Quantum Factoring Algorithm* (arXiv:2308.06572). arXiv. http://arxiv.org/abs/2308.06572

Ross, D. (2024). Game Theory. In E. N. Zalta & U. Nodelman (Eds.), *The Stanford Encyclopedia of Philosophy* (Spring 2024). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/spr2024/entries/game-theory/

Samuelson, L. (2016). Game Theory in Economics and Beyond. *Journal of Economic Perspectives*, *30*(4), 107–130. https://doi.org/10.1257/jep.30.4.107

Shor, P. W. (1994). Algorithms for quantum computation: Discrete logarithms and factoring. *Proceedings 35th Annual Symposium on Foundations of Computer Science*, 124–134. https://doi.org/10.1109/SFCS.1994.365700

Simon, C. (2017). Towards a global quantum network. *Nature Photonics*, *11*(11), 678–680. https://doi.org/10.1038/s41566-017-0032-0

Singh, J., & Bhangu, K. S. (2023). Contemporary Quantum Computing Use Cases: Taxonomy, Review and Challenges. *Archives of Computational Methods in Engineering*, *30*(1), 615–638. https://doi.org/10.1007/s11831-022-09809-5

Steele, K., & Stefánsson, H. O. (2020). Decision Theory. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Winter 2020). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/win2020/entries/decision-theory/

The Game Theorists (Director). (2024). *MatPat's FINAL Theory!* [Video recording]. https://www.youtube.com/watch?v=dgxPlUgIqSA

The quantum vision team. (2019, June). *Quantum Internet: The internet's next big step*. TU Delft.

Townsend, K. (2022, February 16). Solving the Quantum Decryption "Harvest Now, Decrypt Later" Problem. *SecurityWeek*. https://www.securityweek.com/solving-quantum-decryption-harvest-now-decrypt-later-problem/

Tushar, W., Saha, T. K., Yuen, C., Morstyn, T., McCulloch, M. D., Poor, H. V., & Wood, K. L. (2019). A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. *Applied Energy*, *243*, 10–20. https://doi.org/10.1016/j.apenergy.2019.03.111

van Bree, T., Gijsbers, G., Janssen, V., & Goes, M. (2023). *Herijking sleuteltechnologieën 2023. 2023*.

Veritasium (Director). (2023, December 23). *What Game Theory Reveals About Life, The Universe, and Everything* [Video recording]. https://www.youtube.com/watch?v=mScpHTIi-kM

Vermaas, P. E. (2017). The societal impact of the emerging quantum technologies: A renewed urgency to make quantum theory understandable. *Ethics and Information Technology*, *19*(4), 241–246. https://doi.org/10.1007/s10676-017-9429-1

Von Neumann, J., & Morgenstern, O. (1944). *Theory of games and economic behavior—60th aniversary edition (2007)* (60. anniversary ed., 4. printing, and 1. paperback printing). Princeton University Press.

Wehner, S., Elkouss, D., & Hanson, R. (2018). Quantum internet: A vision for the road ahead. *Science*, *362*(6412), eaam9288. https://doi.org/10.1126/science.aam9288

Wheeler, G. (2020). Bounded Rationality. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Fall 2020). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/fall2020/entries/bounded-rationality/

William Spaniel. (2013). *Game Theory 101 The Complete Textbook*. self-published.

Wu, J., & Axelrod, R. M. (1995). How to Cope with Noise in the Iterated Prisoner's Dillemma. *The Journal of Conflic Resolution*, *39*(1), 183–189.

Zamir, S., Maschler, M., & Solan, E. (2013). *Game theory*. Cambridge University Press.