Laura Piispanen:

# Developing Quantum Games, Quantum Art, and Simulation Tools for Exploring Quantum Physics

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# Developing Quantum Games, Quantum Art, and Simulation Tools for Exploring Quantum Physics

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This thesis presents five quantum physics-related game and art projects as annotated portfolios and practice descriptions created using Research through Design methodologies. It also describes the development of a numerical simulation tool for citizen science game development, which has been central to most of the described projects and influenced their design decisions. Additionally, another simulation tool was developed for educational and outreach purposes and is described alongside the project descriptions it connects to. Insights from these experiences led to the design guidelines of quantum physics-related games shared in this thesis.

Quantum physics, a well-established theory describing our world's fundamental aspects, has inspired the creators of games for decades. Many of them have been researchers and educators, but the rise of quantum physics-themed game jams, hackathons, and courses has broadened the audience creating these games, and the online accessibility of quantum computers has further led to the emergence of "quantum computer games", games on quantum computers. These "quantum games" include video games, VR games, board games, and card games with varying references to quantum physics. Despite over 300 categorised quantum games, discussions on their development practices are limited. The increase of attention to the serious use of quantum games by a variety actors highlights this shortcoming.

To address this, this thesis provides practical design guidelines for collaborative projects integrating quantum physics expertise. These guidelines emphasise early, collaborative inclusion of expertise, clear communication of design decisions, the use of playable prototypes and carefully curated visual language in team communication, and strategic use of simulation tools to facilitate successful development. By providing insights into the challenges, opportunities, and best practices of quantum game development, the thesis promotes broader discussions on interdisciplinary science game development and their use in education, scientific communication, and public engagement. The insights shared in this thesis are applicable to various fields related to quantum technology.

Keywords: quantum mechanics, game development, quantum game jam

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TURUN YLIOPISTO
Tietotekniikan laitos

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Tämä opinnäytetyö esittelee viisi kvanttifysiikkaan liittyvää peli- ja taideprojektia kommentoitujen portfolioselostusten ja käytäntökuvausten muodossa, jotka on luotu Tutkimus muotoilun kautta -menetelmällä (engl. Research through Design). Lisäksi se avaa kansalaistiedepelejä varten luodun numeerisen simulointityökalun kehitystä. Tämä työkalu on ollut keskeinen osa useimpia esitellyistä projekteista ja vaikuttanut niiden muotoilupäätöksiin. Lisäksi kahteen esitellyistä töistä liittyy toinen, yleissivistämis- ja opetustarkoituksiin kehitetty simulointityökalu, joka esitellään näiden töiden yhteydessä. Näistä kokemuksista rakentuu tässä opinnäytetyössä jaetut kvanttifysiikkaan liittyvien pelien kehitysohjeistukset.

Kvanttifysiikka on maailmamme peruspalasia kuvaava, vakiintunut teoria, joka on inspiroinut myös alan tutkijoiden kehittämiä pelejä. Kvanttifysiikka-aiheisten pelijamien, hackathonien ja pelikehityskurssien yleistyminen on kuitenkin inspiroinut laajempaa yleisöä luomaan kvanttifysiikasta inspiroituneita pelejä. Ensimmäisten kvanttitietokoneiden saatavuus verkon yli on johtanut "kvanttitietokonepelien" kehitykseen, peleihin kvanttitietokoneilla. Kaikkiin edellä esiteltyihin viittaamme sanalla "kvanttipelit". Kvanttipelejä on kehitetty videopeleiksi, virtuaalitodellisuuspeleiksi, lautapeleiksi ja korttipeleiksi, ja vaikka yli 300 peliä on luokiteltu kvanttipeleiksi, keskustelut näiden pelien kehityskäytännöistä ovat edelleen rajallisia. Kiinnostus kvanttipelien hyötykäyttöön on saavuttanut eri tahojen kasvavan kiinnostuksen, mikä puolestaan alleviivaa tätä puutetta.

Tämä opinnäytetyö tarjoaa käytännöllisiä kehitysohjeistuksia projekteille, joissa hyödynnetään kvanttifysiikan asiantuntemusta. Nämä ohjeet korostavat asiantuntijoiden varhaista ja yhteistyöhön perustuvaa mukaan ottamista, selkeää suunnittelupäätösten viestintää, pelattavien prototyyppien käyttöä ja huolellisesti valitun visuaalisen kielen käyttöä tiimiviestinnässä sekä simulaatiotyökalujen strategista hyödyntämistä onnistuneen kehityksen edistämiseksi. Jakamalla näkemyksiä kvanttipelikehityksen haasteista, mahdollisuuksista ja parhaista käytännöistä se edistää laajempaa keskustelua monitieteisestä tieteen pelien kehittämisestä ja niiden hyödyntämisestä koulutuksessa, tieteellisessä tiedotuksessa ja suuren yleisön osallistamisessa. Opinnäytetyön tarjoamat oivalluksia ovat sovellettavissa monilla kvanttiteknologiaan liittyvillä aloilla.

Asiasanat: kvanttimekaniikka, pelikehitys, kvanttipelijamit

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CHAPTER 1:

# Introduction

As advancements in technologies that allow the control and manipulation of quantum physical phenomena reshape our understanding of the universe, the emergence of quantum physics related games stands as an interesting fusion of entertainment, education and scientific inquiry. Games offer possibilities to simulate the inherent properties of quantum mechanics and a gateway to a world where matter and waves intertwine in extraordinary ways. By transcending conventional gaming experiences, quantum physics related games, *quantum games*, not only entertain but also invite a broader audience to explore the captivating realm of quantum physics. As players navigate the intricacies of the quantum world, they gain insights that are not limited to the game itself but are applicable in other contexts as well. Alternatively, they are able to contribute to scientific work through the game. This types of immersive journeys have the potential to foster a deeper understanding of our surroundings, from the microscopic scale to the unfolding of their connections to aspects like national security, politics, and to the possibilities of emerging workforce in quantum technologies [1], [2]. To achieve these great promises, quantum game development requires expertise and experience based design guidelines. This thesis addresses this need.

*Quantum physics* refers to the physical phenomena and rules governing the world at its most fundamental levels, both on the very smallest and largest of scales. The beginning of the 20th century marked the onset of the first scientific discoveries in quantum physics. Peculiar phenomena such as light releasing electrons from metal in an unexpected manner and small particles acting seemingly like waves puzzled the scientist at the time and induced the beginning of the building of the theory of quantum physics. This era is often referred to as the *first quantum revolution*. Quantum physics offers phenomena that challenges intuition and has since been refined to become the most fundamental of theories describing the world around us.

The study of quantum physics has not evolved in an isolation from praxis, but contributed to the understanding of phenomena observed in the development of electronics and small-scale technologies. This encompasses behaviours observed, for instance, in the development of transistors at increasingly smaller scales. Beyond a certain threshold, conventional potential barriers cease to hold, resulting in the phenomenon known as *quantum tunnelling*, wherein electrons can leak through such barriers. Quantum physics been able to answer the "*Why?*", and is now offering answers also to the question "*How?*". Now, instead of just describing phenomena, the tools offered by the theory of quantum physics are being used to developing completely new kinds of technology, known as *quantum technologies of the second quantum revolution* [3], [4]. These technologies offer ways to manipulate quantum phenomena in a controlled manner.

Quantum computers are an example of the quantum technologies brought to us by the second revolution of quantum physics. They are computational devices that take advantage of quantum phenomena in storing and manipulating of information. Different approaches like nuclear magnetic resonance and light have been researched and applied for the use of quantum computing units, but the most popular technology so far has been the use of superconductivity [5], [6]. In 2019, *Nature* published an article that claimed to demonstrate "quantum (computational) supremacy" over classically working computers, meaning that a quantum computer would have solved a problem impossible for a supercomputer to solve within a lifetime [7], [8]. Although this claim was not accepted by everyone, mutual consensus is that the development of quantum computers represents a significant technological leap. At the time of finishing this chapter the Finnish quantum computing company IQM has published its 20-qubit quantum computer and is promising to deliver a 54-qubit quantum computer this year, thereby leading Finland towards the race of building a working, scalable quantum computer [9].

Quantum physics has long inspired the world of science fiction, games, movies and even marketing themes. Therefore the adaptation to games does not come as a surprise. Quantum games are defined as games that in the context of video games, card games, board games and other games, "*... are games that reference the theory of quantum physics, quantum technologies, or quantum computing through perceivable means, connect to quantum physics through a scientific purpose or use quantum technologies.* " [10]. The motivations behind developing such games have been both serious, as in, educational purposes or for citizen science [10], [11], as well as considered as am inspiring challenge [12], [13].

The motivations for developing serious quantum games have usually stemmed from academic actors. Bringing people to quantum physics through the act of designing and playing games offers the possibility of opening new doors to the theory itself, introducing new problem-solving skills and methods for re-examining the possibilities of the theory. Also, similarly to the case of early digital computer development, games have the possibility to map the extent of the capabilities quantum devices and quantum computers have [14]. Particularly research related to quantum optimal control problems, quantum theory, and quantum algorithms have inspired quantum researchers towards developing serious games, and such projects have shown promise in citizen science use [15]–[17]. Quantum technologies and the study of quantum algorithms also serve other industries in optimising search methods, analysing complex systems and for practices requiring delicate censoring, which emphasises the importance and impact of the field [18], [19].

As new quantum technologies are being developed and built already on a commercial scale, the need for a basic understanding of the nature of quantum physics within engineering sciences – especially in computer science – has increased. However, the usual bottleneck to studying quantum physics has been the fact that the theory, with all its phenomena and peculiarities, is explained using mathematical formalism [20]. This can hinder developing intuition in the theory and even lead to misconceptions [21]–[26]. Interactive simulations show promise in introducing new concepts and teaching basics on quantum mechanics [27]–[34], which has inspired the development of educational games and learning platforms integrating games with learning material [35]–[38]. These immersive and inspiring games and art are seen as particularly important tools for fostering a well-informed society and opening doors towards new employment opportunities in the emerging field of quantum technologies.

The development of quantum computers has received an enthusiastic reception among various industries, media, politicians and educational institutions [39]–[41]. This has cultivated the interest of the general public towards quantum physics. On the downside, the complexity of quantum physics and the largely mathematical study materials often discourages individuals from being inclined to investigate further [20], [42]. What is more, the seemingly convincing use of quantum mechanical concepts with vague references to peer-reviewed scientific articles may be used in a deceptive and misleading manner in marketing materials. For example, such references have been used as a way to argue for the use of questionable practices concerning individual's health in alternative medicines [43], [44]. It is important that the decisions made by governments and other entities regarding the use of quantum technologies are well-informed and inclusive of the people that are affected by them. To ensure that our society is equipped to make the best possible decisions for its future, we need approaches that make the world of quantum physics more accessible. Games in particular have the potential to nurture intuition towards the world of quantum mechanics, like envisioned by John Preskill in 2018 :

> *Perhaps kids who grow up playing quantum games will acquire a visceral understanding of quantum phenomena that our generation lacks.*

> *Furthermore, quantum games could open a niche for quantum machine learning methods, which might seize the opportunity to improve game play in situations where quantum entanglement has an essential role* [4].

Developing quantum games that meet all the made promises require informed, educated and practice based expertise. So far, not much research has been done either on the use of quantum games for serious purposes or the design and development of them. This thesis addresses this shortcoming. In this thesis, we examine the history of quantum physics-related games, referred to as *quantum games*[1]. This term includes games that are inspired by quantum mechanics, that teach or educate about related phenomena, and games that incorporate quantum technologies. We will also introduce definitions of games and the practices of game development.

The study presented in this thesis explores quantum game design practices through immersion in the development of citizen science quantum games and educational quantum games. The presented projects all originated from a collaborative development process involving a numerical simulation tool called *Quantum Black Box* (QBB). This tool was specifically developed for citizen science game purposes between the years 2017 and 2019 and is discussed in Chapter 6. Although the development of this tool did not continue to support further research and improvements, it provided a fertile ground for a multitude of multidisciplinary projects. Consequently, the design of citizen science games, particularly in the context of quantum sciences, provides the specific field setting and cultural milieu for the projects presented in this thesis. We also present another simulation tool designed alongside the

[1] Or *playable* quantum games in comparison to theoretical examinations of games. It is worth noting that this thesis is not about quantum game theory, the discipline combining game theory and quantum mechanics [45], [46], but instead focuses on games that are playable on computers, with cards, or by other means. The intention of quantum game theory is to help deepen the understanding of quantum information processing and quantum algorithms and to help understand the division between the quantum and classical worlds. Games studied in quantum game theory have also inspired experimental realisations [46].

presented projects, where the motivation has been more educational in nature.

Studying these multiple aligned projects helps gain a comprehensive understanding of the design process in quantum game development. The aim is to find suitable design practices for quantum game development that could serve as a guide for science game development, multidisciplinary game development, and quantum software development in general.

This work addresses the research questions of

- What are quantum games?
- How does the inclusion of a numerical simulation influence the development of a quantum game?
- What are the pivotal phases in the development of quantum games?

## 1.1 Outline

The structure of this thesis is outlined as follows. Chapter 2 presents an introduction to basic concepts of quantum physics. Chapter 3 is dedicated to introducing games, game development, and their practices. Chapter 4 introduces the concept of quantum games in the context of playable games and highlights some of the most well-known quantum games to date, explaining their relation to quantum mechanics. Chapter 5 introduces the methods used in the study of developing quantum games and interactive art.

The analyses of the design processes for five game and art artefacts and a simulation tool are presented as self-reflective autoethnographic reports in Chapter 6. This chapter offers an overview of the development of a numerical simulation tool for games and then details the related development processes between 2018 and 2022. Some of the presented projects extended over several years, while others lasted only a few days. The numerical simulation detailed more thoroughly is a citizen science game-motivated project called the *Quantum Black Box* (QBB), and several other presented projects are partly influenced by its development, but QBB has also been incorporated into other playful creations. The projects presented in this thesis are as follows: The citizen science game prototypes *Hamsterwave*, *QWiz* and *Lemmings Condensate* are presented in Sections 6.2, 6.3, and 6.4; an interactive art piece incorporating QBB in it, *Quantum Garden*, is presented in Section 6.5; and the development of *Quantum Playground*, a VR (virtual reality) experience incorporated by a quantum simulation presented in Section 6.6.

From each of these experiences, observations and reflections are reported and viewed from the perspective of a quantum physicist with a background in the study of quantum foundations and interaction design. The main role of the author in the projects has been as a quantum physics expert, with involvement ranging from consulting expert to solo developer and the study therefore contributes to the field of game studies through the exploration of game development as experienced [47]. The observations are discussed in Chapter 7 with the aim to clarify what is needed in the process of quantum game development in terms of game design practices, roles and resources. The outcomes are then offered as design guidelines in Chapter 8 for anyone wishing to develop their quantum game or quantum art projects. These guidelines are presented in a way that can be generalised for all science games and science art projects.

By describing the process, design, and end artefact of the presented projects, it was possible to discuss these games in terms of conceptual themes that may be beneficial for future projects. The presented study provides a better understanding of the complex issues related to the design processes of quantum games, thereby contributing to the future of *science game design* and *quantum software development*.

CHAPTER 2:

# Quantum Physics and Quantum Computing

In this chapter, the basic concepts of quantum physics and quantum computing are presented. It serves as an introductory level entity, focusing on the fundamentals of quantum physics from a phenomenological perspective. First, some basic concepts of quantum physics are introduced in Section 2.1, followed by a concise history of the theory in Section 2.2. This chapters aims to provide means for understanding the quantum physics related concepts addressed in later chapters.

## 2.1 Quantum Physics

Quantum physics is a theory stemming from the need to describe the world at the very smallest of scales, where phenomena do not obey the same laws as the world we witness around us. This means that quantum physics refers to the subatomic scales of the smallest particles, atoms, electrons and protons and to phenomena we are not able to directly witness in our everyday lives. Through the advances in quantum physics-based high-precision measurements used in astronomy and the study of black hole radiation we may say that quantum physics plays an important role also at the largest of scales [48], [49]. The so-called classical world we are used to living in is deterministic, and therefore in principle every single action and occurrence is calculable and predictable, given knowledge of all the variable values related. In contrast, the mathematical theory behind quantum physics – quantum mechanics, more specifically – is fundamentally probabilistic and moreover entails intrinsic principles that restrict our knowledge on a quantum mechanical system [50], [51]. Physical quantities describing a system do not have a definite value in this theory, but are instead described using probabilities dependent on the state of the system. These probability values range from 0 to 1, but this is not a sign of a lack of knowledge about the system, but instead an indication that we cannot claim the quantum system to be in any specific state. Therefore, expectation values and averages of multiple measurement results are used when describing the state of a quantum system.

Quantum mechanics possesses distinctive properties that set it apart from classical mechanics and offers unique features for technology and information technology applications. Without quantum physical phenomena we would not have lasers, transistors, nor superconducting materials and therefore things like MRI imaging or even the modern day tiny computers we have in our mobile phones and smart watches. The following provides an introduction to fundamental quantum phenomena and their implications, particularly in the context of quantum computing, the computational paradigm harnessing principles of quantum mechanics to perform complex calculations.

## Quantisation and Quantum States

Within quantum physics, physical quantities such as energy, momentum, and angular momentum are constrained to discrete values within a bound and finite system. The *(quantum) state* of a quantum physical system is a mathematical description of these quantities. We refer to the minimum amount of these quantities as *a quantum*[1]; any other allowed magnitudes are represented as integer multiples of it. Atoms, which constitute the matter around us, are stable exactly because the energy of an electron is quantised in this way within an atom.

In particular, controllable two-level systems, which exhibit two clearly distinct energy levels or *energy states*, are crucial in the study of quantum information and the development of quantum computers. In this two-level system, the two separate states can be identified with the `0` and `1` familiar to us from standard information processing and are used for the information processing units of quantum computing. These quantum counterparts of classical bits are called *quantum bits*, or *qubits*[2].

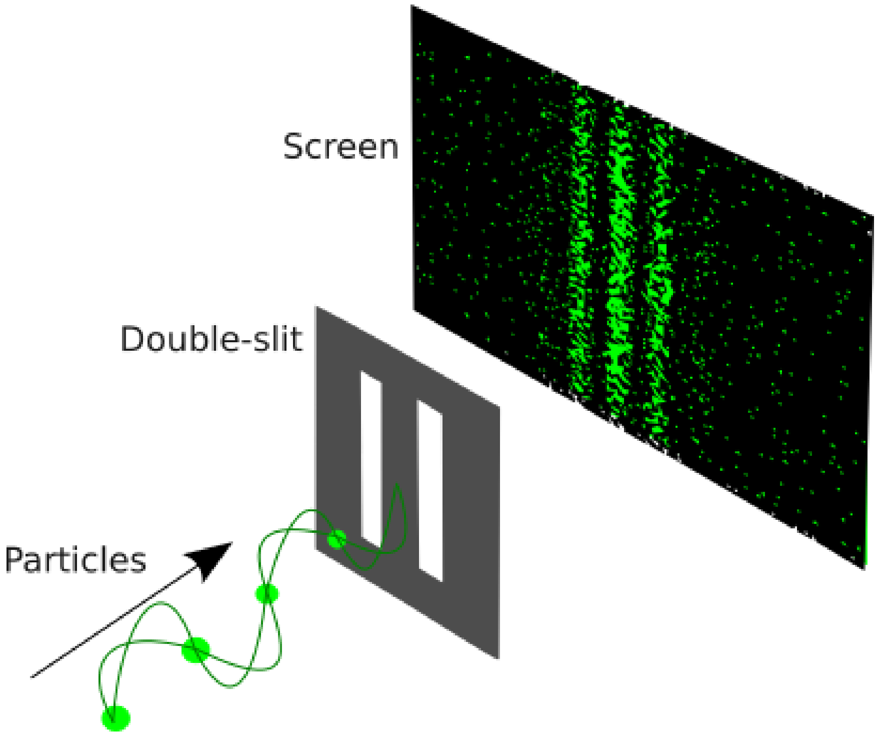
[1] The plural of a quantum is *quanta*.

[2] The alternative spelling "qbits" is also used in some rare occasions.

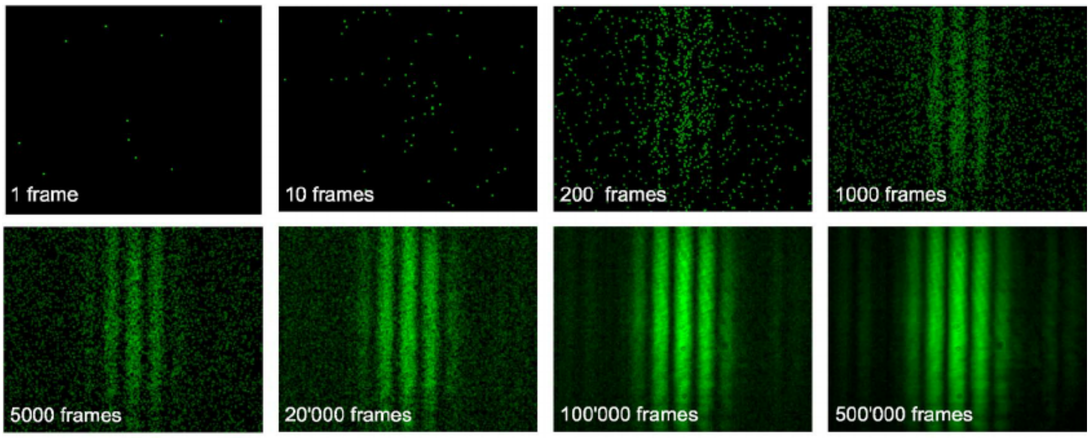
### Wave-particle Duality and Interference

Quantum mechanical systems exhibit characteristics of both waves and particles, a concept referred to as the *wave-particle duality*. In our experience of the world around us, we typically associate waves with phenomena such as light, sound, or electrical signals. We observe how ocean waves interact with obstacles, causing diffraction, or how a stone creates ripples when it is thrown into a pond. On the other hand, we expect solid objects like rocks, buildings, or humans to maintain a well-defined position and not disperse like waves. However, in the realm of quantum mechanics, it is not an either-or situation. For example, a specific frequency of light consists of quanta of certain energy, all multiples of a single quantum of light, which we call a *photon*. We can determine their position using, for instance, a photographic plate or film (although the single photon is lost upon impact as its energy is transformed into chemical and/or physical changes in the material it is absorbed by).

We can experimentally shoot light one photon at a time using precise lasers, and what is particularly intriguing is that even a single photon exhibits wave-like properties. This has been demonstrated through the double-slit experiment, where photons are individually passed through two closely spaced vertical slits onto a screen (such as a photographic film). Instead of accumulating in two distinct vertical rows of marks, they form a pattern that represents wave interference of two sources, one for each slit. In this pattern, we observe dense vertical lines corresponding to positions of constructive interference and dark spots representing positions of destructive interference. Similar experimental setups have been used to demonstrate the same behaviour with electrons, neutrons and small molecules, for example.




(a)




(b)

Figure 2.1: The Double-slit experiment (a) A simplification of the setup in the double-slit experiment. The distance between the slit and the screen in considerably longer than the scale of the image suggests.(b) The formation of the result for a single-shot photon double-slit experiment through time [52].

## Superposition and Coherence

A quantum mechanical object can possess several state configurations simultaneously. For example, it can exhibit the possibilities of multiple energies or positions at the same time. Such states are said to be in a *superposition of states*. Particularly useful superposition states are the so-called *coherent states*, which exhibit a well-defined phase relationship between their components. Coherent states play a crucial role in explaining the *double-slit experiment* (see Figure 2.1). In this experiment, quantum particles (like electrons or photons) are shot at a barrier that has two narrow openings, slits in it. The particles that pass this barrier through the slits hit a screen behind the barrier (like a photo-sensitive film) one by one, but form a pattern that can only be explained using the wave-formalism and interference. We say that the quantum particle thus passes through the double slit in a superposition of passing through the first slit and passing through the second slit, and it interacts with itself in a unique way. When the particle is in a coherent superposition, these ”parts” maintain their phase relationship, leading to constructive and destructive interference that creates the characteristic interference pattern on the screen.

Coherent states also play a crucial role in quantum computing. In certain two-level systems, such as qubits, coherent states enable the transfer of the system between energy levels. Superposition states of qubits offer the possibility of encoding more information than a classical bit could process. By harnessing the wave-like properties of qubits, quantum algorithms can exploit interference and superposition to perform certain calculations more efficiently than classical algorithms.

## Principle of Uncertainty

Fundamental to the probabilistic nature of quantum mechanics is the concept of uncertainty. This not only refer the wide range of possibilities that quantum states of systems can exhibit but also imposes a fundamental limit on the precision of measurements made on them. The *Heisenberg uncertainty principle* states that the momentum and position of a quantum particle cannot be simultaneously measured with absolute precision[3]. Instead, if we obtain precise information about the position of a quantum mechanical particle, this principle tells us that we are unable to gain any information about its momentum at that time. The uncertainty principle extends beyond the determination of momentum and position and applies to other physical quantities as well, including the energy of a state and its lifetime. Consequently, there can be no definite energy associated with a short-lived state of a system.

However, it is important to note that the quantum physical world is not devoid of determinism. On the contrary, we have gained a substantial understanding of the formation and evolution of quantum states, and the limit on the measurement precision of quantum systems is an inherent aspect of the theory. It is precisely when we want to gain empirical knowledge, observe something about the system, and make a measurement that randomness comes into play. Once we measure the state of our quantum system (like, for example, an electron prepared in a certain way), we obtain a single answer from all the possible ones, purely randomly. Performing multiple sequential measurements on a set of identical quantum systems (like identically prepared electrons) will reveal a statistical distribution of these results, which then gives us a better picture of the overall state of such systems. These proportional frequencies become more exact representations of the probabilities predicted by the theory the more data we gather. The probabilistic nature of quantum mechanics is objective.

[3]Originally, Heisenberg introduced the principle without specifying the quantities, but position and momentum are the most commonly known in this context.

### Entanglement and Decoherence

When the physical and statistical properties of one or more particles become intrinsically dependent on each other, to the extent that the state of one particle cannot be described independently, they are said to be *entangled*. Even in the absence of any physical interactions, entangled particles remain deeply connected, including when separated by vast distances. Entangled coherent states play a crucial role in quantum communication protocols, such as quantum key distribution (QKD) and quantum teleportation, enabling reliable encoding and transmission of quantum information over long distances.

Quantum states and quantum phenomena are very sensitive to disturbances from the surrounding environment. As a result, the creation and manipulation of quantum systems must be carried out in highly controlled laboratory settings, with strict measures to minimise external interference. Any interaction with the environment, such as heat (kinetic energy of atoms and molecules) or radiation, can cause decoherence in the system, leading to the loss of its quantum mechanical properties. Possible undesired entanglement with the environment introduces errors and noise in quantum computing calculations, but the flow of the information between the system and its environment may also be controlled and used for various purposes [53].

Entanglement serves as a foundation for various advancements in quantum technologies. Quantum error correction codes heavily rely on entanglement to protect quantum information from errors caused by decoherence and other disturbances. By encoding qubits into entangled states, errors can be detected and corrected, enhancing the overall reliability of quantum computations. Furthermore, certain quantum algorithms, such as *Shor's algorithm* for factoring large numbers, leverage entanglement to achieve exponential speedup over classical algorithms. Additionally, entanglement enables parallel computations and efficient exploration of large solution spaces.

### Observation and Measurement

At the quantum scale, the act of observing an object affects its properties. When a measurement is made on a quantum system, it collapses the superposition of possible states into a single value for a given property. This means that the act of observing a quantum system inherently alters it. A classic example illustrating this is the previously mentioned double-slit experiment, where the presence of an observer or measurement apparatus determining which slit the particle passes through eliminates the interference pattern.

### Tunnelling and Superconductivity

The theory of quantum physics offers much to marvel on, but certain quantum phenomena are particularly often referred to in the context of quantum games; *tunnelling* and *superconductivity*. At the atomic scale, so-called subatomic particles do not necessarily adhere to potential barriers and can sometimes *tunnel* through them, pass these barriers. This means that when, for example, basic transistors are made sufficiently small, they no longer work as reliable barriers to an electric current. Tunnelling is a phenomenon used in very precise atomic scale imaging in scanning tunnelling microscopes. We may even say that life on Earth starts from tunnelling, as nuclear fusion would not be possible without tunnelling at the enormous pressures in the Sun's core.

*Superconductivity* is a property of specific materials in which electrical resistance vanishes at low temperatures, making them superconducting and able to repel magnetic fields. At these temperatures, electrons pair up, and these pairs act as charge carriers. Some of the most powerful magnets in nuclear magnetic resonance (NMR) equipment, for example, are electromagnets made using superconductors.

## 2.2 From Quantum Physics to the Formation of Quantum Information

The history of the theory of quantum physics began with the arrival of observations of phenomena that were not expected based on the predictions existing at that time from the so-called classical theories. For long, scientists had debated over whether light is wave-like or a stream of "corpuscles", like Isaac Newton described it. In Thomas Young's 1807 lectures, he presents the double-slit experiment, thereby illustrating the dual nature of light as both particles and waves.

In 1900 Max Planck conducted research on black body radiation. Black body radiation refers to the electromagnetic radiation emitted by an idealised object known as a black body, a physical object that absorbs all incident electromagnetic radiation (light) and re-emits this energy perfectly according to its temperature. Charcoal presents itself as a simplified example. As the temperature of a black body increases, the intensity and spectrum of the emitted radiation change. Planck noticed that radiation would not be emitted in a continuous manner but was instead quantised. From this observation he concluded that by its nature, energy must be quantised into discrete packages, quanta. This revolution has widely been referred to as the foundation for the development of quantum mechanics. In 1905 Albert Einstein used this hypothesis by Planck to explain the photoelectric effect. The photoelectric effect is the phenomenon where a metal surface emits electrons when it is exposed to certain wavelengths of light. Einstein reasoned that light would therefore also be composed of particles with discrete energies. These particles of light were later named *photons* by Gilbert N. Lewis in 1926.

Based on the principles of quantisation proposed by Planck and Einstein, Niels

Bohr suggested a new way of describing the atomic structure in 1913. It was to account for the spectral lines observed in atomic spectra of Hydrogen, and did this by suggesting that electrons of an atom would orbit the nucleus in discrete energy levels, rather than in a continuous manner. By absorbing a photon with a specific energy, an electron would gain this energy and be able to transform to another energy level. And by emitting a photon, an electron would fall to a lower energy level, with this photon corresponding to a peak in the atomic spectra. Bohr's model would also account for the stability of atoms, as well as the size of atomic radii, and was an important step towards understanding the structure and behaviour of atoms in an improved manner.

In 1924, Louis de Broglie proposed that if light could behave like a particle, then perhaps particles like electrons could equally well behave like waves. In his hypothesis, he suggested that a wavelength be associated with these particles in a manner that would be proportional to their energy.

After years of experiments, the mathematical formulation for quantum physics, namely *quantum mechanics*. Werner Heisenberg proposed matrix based mechanics in 1925. To allow for the description of particles as waves, Erwin Schrödinger introduced wave mechanics, that relied on differential equations, as an alternative only a few months later in 1926. Though these two formalisms were developed independently, they have been proven to be mathematically equivalent and provide tools for addressing different, equally important aspects of quantum mechanics.

A little later, in 1927, Werner Heisenberg formulated the uncertainty principle, which laid the groundwork for quantum mechanics to be realised as a probabilistic theory. The formation of the theory of quantum physics during the first half of the twentieth century has later been named as the *first quantum revolution*.

In a seminar paper from 1935 Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) discussed a thought experiment involving two physically separated particles. They present the concept of entanglement, in which these two particles become correlated in a way that allows predictions about one particle based on the measurement of the other. As such nonlocal effects would violate Einstein's theory of nonlocality, EPR suggested that quantum mechanics was an incomplete description of reality, but could be explained by hidden variables. Hidden variables would mean assuming predetermined properties of the particles, that would be independent from the observation.

In 1964, John Bell proved a theorem questioning the idea of hidden variables. His theorem showed that there cannot exist a local hidden variable theory that could reproduce all the predictions of quantum mechanics, including its nonlocal nature. Although Bell's theorem has been experimentally confirmed through various experiments, the EPR paper raised fundamental questions about the nature of entanglement, and its implications for our interpretation of quantum mechanics. Bell's theorem had profound implications for quantum information theory. It showed that entanglement is a fundamental aspect of quantum mechanics and that quantum systems can exhibit correlations that are stronger than any classical correlation. These nonlocal correlations are at the heart of many quantum information processing tasks, such as quantum teleportation, quantum cryptography, and quantum computing.

In the early 1980s, significant milestones in the development of quantum computing were achieved. In 1982 Paul Benioff introduced a quantum-mechanical model of the Turing machine, while Richard Feynman and Yuri Manin put forward the concept of utilising the principles of quantum mechanics to simulate phenomena that were beyond the reach of classical computers [54], [55]. Feynman envisioned quantum computers to bring a critical advantage over existing computers in solving the quantum physics problems that physicists and chemists were trying to solve. His reasoning was simple:

> *Nature isn't classical dammit, and if you want to make a simulation of Nature you better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy* [56].

A major breakthrough came in 1994 when Peter Shor devised an efficient quantum algorithm capable of solving the challenging problem of prime factorisation. This problem has no known efficient classical algorithm and is therefore widely used in encryption algorithms today. This notion underlined the possibilities and risks quantum computers would bring along them.

We have since then come through a long way and have already entered the *second quantum revolution*, where the knowledge, technologies and scientific breakthroughs have allowed the control and manipulation of quantum phenomena in great precision. This era has brought to us advantages in quantum metrology and sensing, quantum simulations, quantum communication and quantum computers to the field of quantum computing [3], [57]. As we shall learn from this thesis, quantum computing and the emergence of quantum computers have motivated and impacted many quantum game projects.

CHAPTER 3:

# Games and Game development

Playing is central to human nature, and different types of games are an essential part of life starting from early childhood. Play is not just a trivial pastime but a fundamental and essential aspect of human life and has influenced and shaped human culture throughout history [58]. Playing has also been claimed to be biologically inherent in both animals and humans, and considered a necessity for healthy psychological and social development [59]. The earliest verified archaeological find of a game piece was found in Jordan and dated to the Neolithic era [60]. *Mancala* and games similar to *Checkers* can be found depicted on Egyptian murals played by married couples [61, p. 395, 397]. This is a remarkable manifestation of how deeply games and play have been and will be part of our culture.

Today, most of us think of games as tabletop games, cards, and increasingly often as digital games. An estimated 3.26 billion people play video games, with the global average time spent playing video games ranging from 6.33 to 8.45 hours per week in recent years [62], [63]. The variety of game genres vary between puzzles, role play, platformers, strategy and simulation, adventure, to name a few, and any combination of these. Academic attempts for finding ways to characterise different types of game and play introduce topologies for the pace of the game, team composition, spatial perspectives determinism [64]. More over, the very definition of game and play has constituted many attempts of listing features or conditions [58], [65]–[71]. For most of these definitions, the essence of a game boils down to having set rules of a game, clear goals and challenges like puzzles or enemies.

Although smart devices are a part of the everyday lives for most people, the history of digital computers is rather young compared to the history we have with games. Since the inception of digital computers in 1950s, games have also been played on them. Creating games for computers requires a level of familiarity with the underlying technology, and furthermore, creating games that are intriguing and capture the players' interest necessitates design and development skills acquired through both theory and practice. This chapter introduces only the very first steps in the history of digital games alongside with the development of the first digital computers. This concentration is inspired by the current state of quantum computers taking their very first steps. We then pay particular attention to the study of science related games and examine the roles and phases in game development.

## 3.1 The Early History of Digital Games

The birth of computer games is closely intertwined with the development of digital computers. The *Atanasoff-Berry Computer* (ABC), constructed between 1937 and 1942 by John Vincent Atanasoff and Clifford Berry at Iowa State University [72], marked the advent of digital computers. ABC was purposefully designed for solving linear equations and introduced binary digits (*bits*) for data representation and capacitors for data storage. Another significant milestone was the invention of the first patented digital computer, *ENIAC*, by J. Presper Eckert and John Mauchly at the University of Pennsylvania. Similarly, in 1943, Tommy Flowers developed the electronic digital computer called *Colossus* at Bletchley Park, United Kingdom [73].

In 1950, a computer named *Bertie the Brain* was specifically created to showcase its capabilities to the general public by playing the game *Tic-tac-toe*. Utilising vacuum tubes and light bulbs, it demonstrated the practical application of these technologies. Following this, in 1951, *Nimrod* played the game *Nim* using vacuum tubes and light bulbs. The development of these games aimed to educate and illustrate the then abstract concepts of programming principles and algorithms. Soon after, the first game on a general-purpose computer[1] was a variation of *Tic-tac-toe*, created in 1952 at Cambridge University as part of the research project *OXO*, which focused on exploring human-computer interaction on the *EDSAC* computer. While

[1] In comparison to the earlier computers, that were used for more specific tasks.

*EDSAC* also employed vacuum tubes, it incorporated cathode-ray tube displays, a technology familiar to television and personal computer users until the mid-2000s when newer technologies replaced them in the market.

In general in the 1950s and 1960s, writing games for fun was not encouraged as computer time was very expensive and not easily available to many. Instead, games developed during that era usually had a serious purpose behind them [73]. These games continued to be about showcasing new technologies, educating the public about them, or researching the abilities of the technology itself, like the development of AI for playing Checkers, by IBM Research. Another relevant motivation was the training of soldiers through simulation games of dangerous environments. Simulations and digital war games played an important role in enhancing the US Army's ability to face ongoing problems and future planning already in the 1960s and the 1970s [74], [75].

In the development of entertainment games, the first game to allow for two players to simultaneously play and compete with each other was *Tennis for Two*. It was developed in 1958, by Willie Higinbotham at Brookhaven National Lab for a computer designed for calculating ballistic paths of missiles. The players would control the movement of a ball-like object on an oscilloscope display with the use of custom controllers on a tennis court viewed from the side [73]. The value computers could provide for game development was explored more in 1962 with the publication of *Spacewar!*, a space battle game for two players written by Stephen R. Russell, J. Martin Graetz, and Alan Kotok [73]. It was developed not only to test out MIT's new PDP-1 computer and showcase its capabilities but for attracting a wider audience. What makes *Spacewar!* stand out in the history of games is that it was not an implementation of an existing game, but an original game playable exclusively via a computer interface: the player-controlled spaceships were under the influence of a gravity field caused by a star.

*Spacewar!* highlights an important factor in the search for what a computer can offer for games: immersive and interactive experiences. The narratives in movies and most books and plays would follow a linear narrative. Narrative-driven games in contrast allow the interaction with the story, thus allowing for interruptions and exploration. In 1976, early text-based adventures like the one *Adventure* (also known as *Colossal Cave Adventure*) was developed by Will Crowther and later expanded upon by Don Woods. The game is often cited as the first text adventure ever created, but has also been described as a "colossal cave game" or as an "interactive fiction game" [73].

It took some 14 years after *Tennis for Two* that a totally different ball-passing-game, *Pong* was released by Atari and marked the beginning of the video game industry [73]. From this point onwards, a growing variety of games as well as game consoles have been competing in the growing markets of digital games of today. The development of technology available for consumer use has enhanced the world of digital play in a way that has allowed games to explore their capabilities all the way from arcade games, and the first home consoles to VR games and mobile games. Interestingly enough, games have further enhanced the development of computers and software by, for example, influencing the development of the graphics processing unit (GPU) of computers [76].

## 3.2 Science Games and Citizen Science Games

In game studies, the terminology associated with games and their study has developed alongside the discipline itself [71], [77], [78]. A significant academic endeavour has been the identification of subcategories of games, including games for entertainment, educational games, and science games, based on their intended uses. However, the labelling of these games does not always align with their actual usage. Science games, for instance, have often been described as educational games specifically focused on natural sciences and primarily designed for children as opposed to being games relating to science and research in general [38], [79]–[82].

To address this issue, a broader definition of a *science game*, encompassing games that contribute directly or indirectly to scientific work was suggested in 2022 [10]. This definition is based on the concept of a *science game jam*, which refers to a game jam event that facilitates collaboration between game developers and scientists to create games that contribute directly (e.g., solving research questions) or indirectly (e.g., building awareness or teaching scientific topics) to scientific work [12]. More generally, a *game jam* is an event designated for collaborative game development usually under restrictions on time, certain theme or technology available [83].

> *Science games are games that contribute directly or indirectly to scientific work.* [10]

Science games can be further categorised based on their goals, including training, inquiry, professional simulations, epistemic games, embodied system games, and research collaboration games, highlighting the diverse range of game formats available in digital science games [84].

In a broader context, 'serious games' or 'applied games' refer to games designed for specific purposes and it is often emphasised that serious games are created with the goal of achieving a particular outcome, beyond mere enjoyment [85], [86]. We could therefore say that science games are serious games, where the purpose is scientific contribution. In addition to science games, the category of serious games encompasses games with diverse aims, including social impact, problem-solving research, public education, marketing, advertising and occupational training [87], [88]. An example of a serious game that would not be labelled a science game is *PeaceMaker* by ImpactGames in 2007, a government simulation game simulating the Israeli–Palestinian conflict for general awareness [89]. Still, the study of serious games has also primarily focused on educational games. Ratan and Ritterfeld defined serious games as a genre that focuses explicitly on education, while Rodrigues described them as tools for developing creativity and innovation competencies [90], [91].

Educational games are designed with specific educational goals in mind, placing emphasis on the game's content and message. They may be about teaching scientific principles or technical skills and be therefore considered to contribute indirectly to scientific work, making them also science games in the context discussed here. But educational games exist also for the purposes of learning vocabulary, leadership, soft skills or understanding financial and economical principles [88]. When developing these games, creators must be mindful of both the process of game-based learning and the role of game-based pedagogy [92]. This entails considering the game's use and evaluating it from the perspectives of both the learner and the teacher. It is important to assess if the game enhances learning and effectively addresses the intended learning objectives, as well as whether it improves teaching practices and overall teaching effectiveness. As these games are often suggested to be played in classrooms or other supervised environments, and the motivation for playing them is extrinsic, designing entertainment aspects are at times seen as a secondary focus [88], [93].

Games that contribute *directly* to scientific work are typically referred to as *citizen science games*. *Citizen science* is the act of involving members of the general public in scientific studies or research [94]–[98] and *citizen science games* offer an interactive tool for such purposes [99], [100]. In practice this means that these people are collecting, manipulating and/or analysing valuable data supporting university-level research. While machine learning has made rapid progress in tasks like image recognition and labelling, people are still outperforming computational technologies in certain tasks. At the same time, collecting and classifying large sets of data often requires time and resources that are unavailable for many research projects and therefore motivated non-experts have been engaged for such tasks through citizen science [101]. *Gamifying* otherwise laborious tasks enhances participant engagement, motivation, and enjoyment [102]. Therefore citizen science games offer a highly efficient tool for research, when carefully organised to provide intuitive problem solving tasks that are directly connected to the model being researched. For these games, the motivation to play them is usually intrinsic and stems from the player's interest towards contributing to a scientific topic [103], [104]. Still, the game always needs to be attractive, engaging, and thus ensure the reliability of the data being generated [103].

## 3.3 Game Development Processes

Developing a simple game might be a quick process and may be done in under an hour, especially when one has the experience, knows their development tools and has a clear vision of what they are doing [105]. Still, sometimes coming up with an idea for a game might already by itself take longer than this. Developing a game that constitutes an enjoyable experience demands a lot of planning, designing, and testing, let alone coding and problem-solving, and these aspects are considered differently in solo projects, micro-projects, and larger-scale projects. For this section we introduce the basic structures of game development in a manner that is inspired from indie game development and *game jam* development, but start by some general software development principles used widely in the game industry. Game jams are "*accelerated opportunistic game creation event(s) where a game is created in a relatively short timeframe exploring given design constraint(s) and end results are shared publically´´* [83]. The following development principles highlight the importance of iteration, a principle important in a game development process.

Many practices in game development stem from general software development practices, which provide structure to the process [106]. *Agile software development*[2] is a software development approach characterised by iteration and incrimination, with a strong focus on flexibility, collaboration, and continuous improvement. It is founded on the Agile Manifesto, which is a collection of ideals and principles that govern the development process [107], [108]. By fostering flexible planning, evolutionary development, early delivery, and constant feedback, agile software development tries to alleviate the limitations of traditional, sequential software development methodologies. It promotes cross-functional team collaboration and self-organisation, with the goal of delivering high-quality software in small, frequent increments. Agile techniques like Scrum, Kanban, and Extreme Programming (XP) give frameworks and practises for putting Agile concepts into action.

*Scrum* is a specific agile project management framework, whose core ideas are favoured by many in the field of game development [109]–[111]. It is designed to enhance collaboration, adaptability, and productivity in software development and other complex projects. The idea, in short, is to go about the development of the application in phases, *sprints*, where the outcome is repeatedly evaluated as a team and the next step(s) are planned and communicated clearly. The advantage of the procedure is that in bigger teams it is freeing the sub-teams/participants to work on assigned tasks. Bringing the involved participants together to agree on possible changes and next steps ensures the process has a structure and is easily monitored. Such an approach may prove beneficial, particularly when there is a specific need for efficiency, like for example in time-restricted game jam events. It necessitates on distributing clear roles for the project team members and/or sub-teams for them to be able to work independently during sprints. On the other hand, pre-defining strict roles may be a hindrance creative opportunities, that bloom from

[2] To differentiate it as a proper word and to underline its relevance as a distinct approach, the term “Agile” is frequently capitalised.

cross-disciplinary collaboration [112]. This emphasises the importance of openness, collaboration and cross-disciplinary meetings in game developing processes and is usually a vital component of successful game jam experiences [47].

Scrum emphasises the self-organisation of cross-functional teams and promotes frequent communication and feedback through frequent meetings, sprint planning sessions, and sprint reviews. Though one of the key values of the Agile manifesto is "Working software over comprehensive documentation", it does not mean to discard all documentation. Key elements of Scrum include a clearly structured backlog, a prioritised list of work items, and the use of visual boards like *Kanban* to track progress. For game development, in particular, a game design document (GDD) drives the overall development from start to finish as is to be referred to when possible challenges questioning the design appear. The Scrum process fosters flexibility by allowing teams to adapt to changing requirements and encourages continuous improvement through regular retrospective meetings. By promoting transparency, collaboration, and iterative development, Scrum provides efficiency to a project execution, early delivery of value, and the ability to respond effectively to evolving project needs.

The following suggested possible collection of steps and concepts for developing a game compiled in a way that supports the structure of a Scrum process and is inspired by game jam development [47], [110]. It is important to underline that these phases are not strictly linear and may overlap or require revisiting throughout the game development process. Flexibility, adaptability, and a user-centred approach are key principles that underpin each stage.

## Design

When developing a game, it is crucial to establish a clear concept idea, the overall vision, and goals for the game. This includes identifying the target audience, core gameplay mechanics and rules, the desired player experience, and agreeing on roles, tools etc. to achieve these aspects. By addressing these key elements, the foundation for a well-defined concept that will guide the overall development process is established and is advised to be documented on a game design document for process guidance. This document will guide the design of the balance between challenge and award of the game mechanics, the design of the visual experience of the game, the controls the player is able to use and the overall narrative shaping the player experience.

Creating a story behind a possible main character sets a stage for the narrative of the game, which builds to the emotional journey of the game. Considering light, colours, and sound all build up to the overall mood and atmosphere that is perceived through the game, so agreeing on the aesthetic and visual language of the game helps convey and support the narrative and is equally important to the game design document. Aligning the narrative elements of a game with its mechanics helps create a cohesive experience for the player. After the initial design phase, the conceptual ideas are further refined and translated into a concrete plan and any possible addition or removal of a feature can be weighed upon referencing the design document.

Especially for games that are designed with a serious purpose, there are several important additional considerations. For a serious game, you must evaluate the significance of the possible scientific correctness relative to other aspects of the game. Additionally, the underlying reasons for playing the game should be explored. Often at some stage of the development, a decision is to be made between focusing on creating an immersive experience and delivering educational content. Discussing and agreeing on all these aspects help define the ultimate objective of the game.

Upon revisiting the design during subsequent iterations, it will become clear which aspects are feasible to further develop within the given time frame and available resources. It is also essential to reassess the objectives: Are they overly ambitious, or should they in contrast be heightened to reach the full potential the project can offer? Will technical constraints force or steer the game in a new direction? Might certain demands that were initially established or outlined in earlier iterations be discarded? Occasionally, one might need to abandon an idea that was initially met with great enthusiasm to create an enjoyable and playable game experience.

### Brainstorming and Developing Ideas

When starting from scratch, armed only with unbridled enthusiasm to create *something*, finding a starting point can feel like a daunting challenge. Within a team, there's typically an individual who suggests an idea, which then evolves through collective effort [113]. However, that initial spark of an idea needs to originate from somewhere, and fortunately, there exists a variety of practices, tools, and experiences on idea generation [113], [114]. For instance, game idea generation games or word cards can serve as stimuli to ignite the creative process [115], [116]. Especially for projects where one of the design constraints includes challenging topics, such as quantum physics, a straightforward approach might be to build upon existing games, movies, well-known stories, or captivating lore, which can provide a helpful starting point [117]. Should there be specific constraints tied to the game, such as a theme, simulation, or technical limitations, it is crucial to ensure that all team members are aware of them.

Starting from an initial idea, a theme, or a set constraint, a *brainstorming process* may be initiated to explore the potential manifestations of the game [110].

Brainstorming aims to generate a large number of ideas around the initial idea in a collaborative and open environment, where thoughts, innovative suggestions, and diverse concepts can be shared freely without judgement or criticism, and are refined later. The aim is to explore different possibilities, explore unique game mechanics, narratives, art styles, and gameplay elements that can contribute to the development of engaging and unique game experiences. It is therefore important to remain open-minded, even to seemingly unconventional or initially perceived as “bad” ideas, as these ideas may evolve into tangible concepts, particularly when multiple creative minds are involved. After the initial brainstorming, this method can be highly beneficial in attacking any possible challenge along the development process.

In team projects, communication is of particular importance. Finding tangible means of conveying the idea further is important [110], [114]. Visual aids like mind maps, concept boards, and drawings are important to support communication. Focusing the brainstorming from a theme-constrained view can be successful in bringing several interesting ideas and in directing the idea creation towards the starting constraint(s) [118].

It is greatly advisable to produce a paper mock-up or employ basic game engines to develop a test interface, but a mock-up may be anything that serves the purpose of communication as well as prototyping the main functionalities of the game interface and its use [119, p. 158][120]. At a later stage, sharing playable versions of the prototype with the team serves this purpose. Building a mock-up greatly helps conveying the idea to others and enhancing clarity, even for the originator of the concept.

### From Prototyping to Building

Once the initial design has been refined, the roles of people contributing can be divided and the development phase begins. This stage involves the actual implementation of the game, including coding, artwork creation, level design, and audio production. Many of these steps can be advanced independently by separate sub-teams of individuals and then be brought together and shared in meetings according to the sprint plan. This iterative meeting cycle fosters efficient collaboration between different team members and is crucial to ensure the smooth progress of development.

Depending on the scale of the development, a game developing team may consist of hundreds or even just one person. In a bigger project, there might be several individuals with identical job descriptions working together in a sub-team as where a smaller project might consist of individuals filling multiple roles [47, p. 156]. The game industry is full of different types of roles for which the job descriptions may vary or overlap depending on the projects the company is undertaking at the time of recruitment. For the purpose of this section, we shall go over the most obvious roles or role types inspired by the simplicity of the role division in many game jam teams. For more massive projects that involve a number of people each with specific expertise and related tasks, it is optimal to have a producer managing the overall project and delegating the right people to the right tasks.

A *game designer* is someone responsible for the concept of the game and working with the rest of the team with fixing or changing anything in the game itself. For serious games, a field expert like a physicist or an eLearning expert plays an equally wide role, as their responsibility is to ensure the connection to the studied problem or idea to the taught stays respectful. It is therefore important for the game designer and the field expert to collaborate seamlessly through the project.

A *programmer* is usually someone responsible for the handling of the game engine and the code related to the project. It is worth noting that coding knowledge is not a prerequisite for game creation. Numerous user-friendly game engines with graphical interfaces have emerged, many of which are freely available. Examples include Bitly, GB Studios, Construct, and Twinery. This role may in special purposes include responsibility of integrating a numerical simulation meant for the development of a serious game like a citizen science game. It is particularly important to keep close communications with the field expert to ensure the simulation is used as supposed. Programming might include a set of sub-roles such as engine writing, creating an artificial intelligence, planning the call structure etc. The programmer basically creates the bones and structure of the game, where as an *artist* or a *visual designer* is required for producing the visual elements visible for the player and a *sound designer* plans for what the player is able to hear. Similarly to other roles having possible subroles, the design of the visuals and the sound world include designing the visual concept, texturing, animation, communicating about the game environment, dialogue and choices, all important aspects for creating the overall mood of the game.

Refining the game's final aesthetics, audio, user interface, and overall presentation ensures the immersiveness of the game, but should serve both the game design as well as the narrative of the game. It involves enhancing the visual appeal, optimising performance, and fine-tuning the gameplay experience. A *narrative designer* ensures that the overall experience of the game world is coherent with the game design as the player enters the world created within the game. This role sometimes coincides with the *writer* of the game, but these roles should not be confused [121]. The role of the writer may concentrate of actual writing of dialogue, where as the narrative designer might have additional responsibilities on working together with the visual designer.

It is also important to test the prototypes and iterations of the game throughout the development process. When possible, getting people from the target audience to play the game and verbalise their thoughts on it should be organised. Thoroughly planning the game concept and its underlying structure is crucial to avoid investing effort into a venture that may subsequently prove futile and incongruous with the overall game vision. Attention to detail and meticulous refinement contribute to a polished and immersive final product.

Once the game is considered complete, it is ready for release. For commercial projects this phase involves marketing, distribution, and making the game available to the intended audience. Launch strategies, promotional campaigns, and distribution platforms are crucial considerations during this stage and are worth considering even for non-commercial games, when there is a serious purpose related to the game. This is to ensure the acquiring of invested players for citizen science games in particular. The post-release phase involves ongoing support, updates, and community engagement. It includes addressing user feedback, providing patches or expansions, and fostering an active player community. Continual post-release efforts contribute to the longevity and success of the game.

Chapter 4:

# Quantum Games

In this chapter the history of quantum physics related games, namely *quantum games*, is presented and a formal definition is provided. While the number of these games have doubled within the last few years, the history of quantum games can be claimed to reach as far back as the early 1980s [10], [122]. With a growing interest towards both the citizen science and educational use case for quantum game development, it is evidently important to acknowledge the variety of games that exist in relation to the theme. As we learn in this chapter, many quantum physics related games are not educational, research-motivated, or else created with serious or applied purpose, nor do they typically have any use for such application. However, through exploring the history of quantum games within an expanding ludosphere, inclusive of games for entertainment, we can draw inspiration from and further develop the concepts, themes, and mechanics already found in existing work, therefore providing relevant background and support for the quantum games of tomorrow [123].

## 4.1 Defining Quantum Games

Previous academic work detailing the concept of quantum games has typically focused on describing only those games with a serious purpose, especially concentrating on educational purposes [15], [38], [124]–[126], which may present the perspective that quantum games are always for educational or scientific purposes. In the following definition, the notion is expanded by looking at the entire ludosphere through the many different motivations that have inspired (quantum) game developers. Beyond the aforementioned serious use cases, these motivations include testing the abilities of quantum computers to benefit future games, and utilising quantum physics to provide thematic or mechanical flavour in commercial games.

Over 300 games have referenced quantum physics to date and are listed publicly in reference [122]. The study of these games has led to the definition of quantum games as presented by Piispanen et. al. 2022:

> *In the context of video games, card games, board games and other games, quantum games are games that reference the theory of quantum physics, quantum technologies, or quantum computing through perceivable means, connect to quantum physics through a scientific purpose or use quantum technologies* [10].

These presented aspects are referenced as the *dimensions of quantum games*, which are sought either through the gameplay or any of the peripheral material (see Table 4.1).

Table 4.1: The dimensions of quantum games, based on an analysis of 250 games as described by Piispanen et al. (2022) [10].

| **DIMENSIONS OF QUANTUM GAMES** |
|---|
| **Perceivable dimension of quantum physics:**<br>The reference to quantum physics in the game is perceivable by interacting with the game or with its peripheral material<br>(such as rule books, descriptions, etc.) |
| **Dimension of quantum technologies:**<br>The game incorporates use of quantum software or quantum devices either during the gameplay itself, or during<br>the development of the game |
| **Dimension of scientific purposes**<br>(in the field of quantum physical sciences):<br>The game is intended to be an educational game, a citizen science game, uses a tool designed for such games<br>or otherwise has a purpose towards a scientific use in the study<br>of quantum physics |

## 4.2 History of Quantum Games

As seen in Chapter 3, games exist in many forms. Although most of the known quantum games are digital, quantum card games and quantum board games have also been developed [10]. An open online listing including most known quantum games has been collected since 2017 through the Quantum Game Jam -events, academic papers, academic conferences, public outreach projects, and other online sources, and covers a variety of game types [12], [122]. In this section, we will go through a sample of them by examining their possible purpose. We explore the ways games have been referencing quantum physics, connected to quantum simulations, and played on quantum computers. There exist some games that are using the word “quantum” without a clear, perceivable dimension of quantum physics in them, like in the video game *Quantum of Solace*, where (as in the movie) the word “quantum” refers a minuscule amount of something, solace or consolation in this case. An earlier instance, the game *Game Over II*, a space adventure shooter released by Dinamic Software in 1988, had a C64 version titled *Quantum*, but the connection to quantum physics was merely superficial as to relation to quantum physical phenomena or the theory is present, other than the title. The inspiration for such games might have originated from other concepts related to quantities or sudden changes and were added to boost a sci-fi theme rather than genuine quantum physics principles. Such games have been excluded from this examination, as they do not fit the definition of quantum games [10].

In a broader context, the genre of “Quantum fiction” has been described by novelist Vanna Bonta as a genre that encompasses “the realm of all possibilities,” in contrast to Ray Bradbury’s definition of science fiction as a “depiction of the real.” This genre has also found its way into modern commercial computer games, with titles like *Quantum Break* blurring the line between quantum games and quantum fiction. While quantum physics in fiction often contains misconceptions or replaces magic with quantum, thus creating a disconnect from experts in the field, *Quantum Break* stands out as an exception, as the developers sought consultation from a theoretical physicist working at Cern during its development process (refer to Figure 4.1a). The game touches heavily on the concept of time travel and manipulation of time, and though the game does not aim at being scientifically rigorous, the physics expert Syksy Räsänen did use a considerable amount of time to design a scientific riddle for the game, an equation with a small error to solve (see Figure 4.1b) [127]. Piispanen et. al. have concluded that *Quantum Break* is a quantum game through its design of perceivable elements of quantum physics references [10].

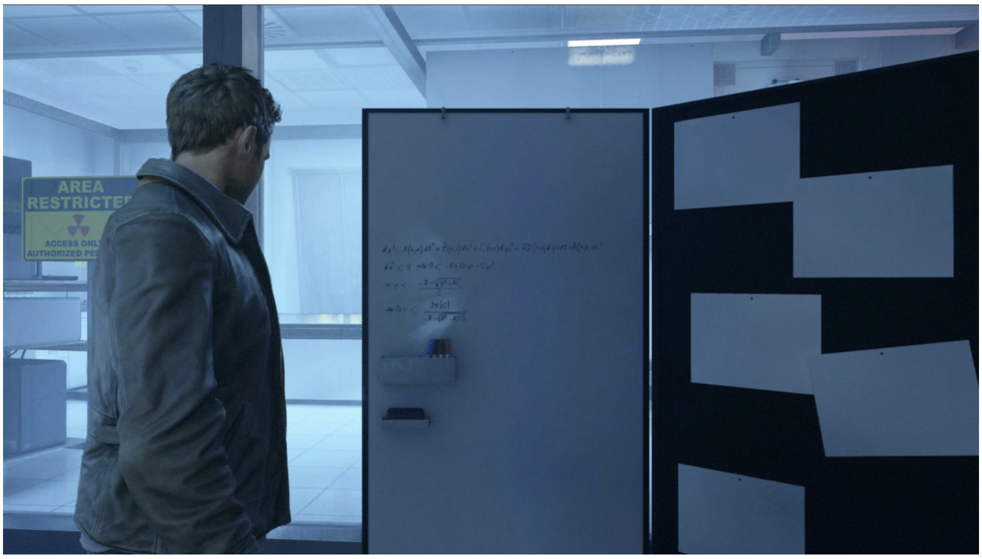
The earliest references to quantum games can be traced back to the 1980s, with the first commercial game featuring the term "quantum" in its title being *Quantum*, released for Atari in 1982. This game is set in the subatomic world of particles, where players are tasked with capturing them using the optical trackball provided in the arcade machine. The incorporation of quantum physics concepts in the game design aligns it with the definition of quantum games [10].

### 4.2.1 Games for the Study of Quantum Physics

Digital games have the potential to extend beyond fiction. They can serve as visual tools that enable direct player interaction with simulated quantum phenomena, thus offering a unique opportunity for learning and mental model development [124]–[126]. Specifically, interactive tools dedicated to simulating and visualising quantum phenomena have successfully capitalised on this potential, contributing to reinforcing learning and constructing mental models [27]–[29].

Educational purposes have been one of the earliest and most prevalent reasons for developing games in the context of quantum physics. While quantum mechanics is primarily taught through traditional means such as textbooks, lectures, and, in recent times, e-courses, the lack of real-life references to quantum phenomena in our daily experiences often presents challenges and can lead to misconceptions when studying these abstract concepts [21]–[26]. Games, in contrast, exhibit promise in introducing new concepts and teaching fundamental principles of quantum mechanics by offering means to interact with numerically simulated phenomena. *Quantum*

(a)




(b)

Figure 4.1: (a) Screenshots from the game *Quantum Break* (*Remedy Entertainment, Press kit*). *Quantum Break* is a science fiction action-adventure third-person shooter video game, where the protagonist is able to control the flow of time. (b) In the game *Quantum Break* a scientific riddle is part of the narrative of the game.

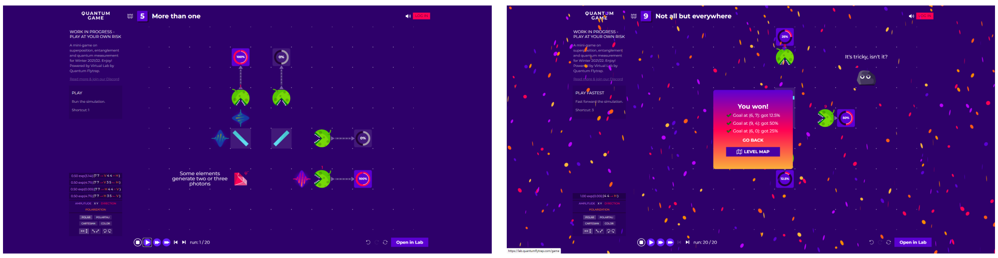
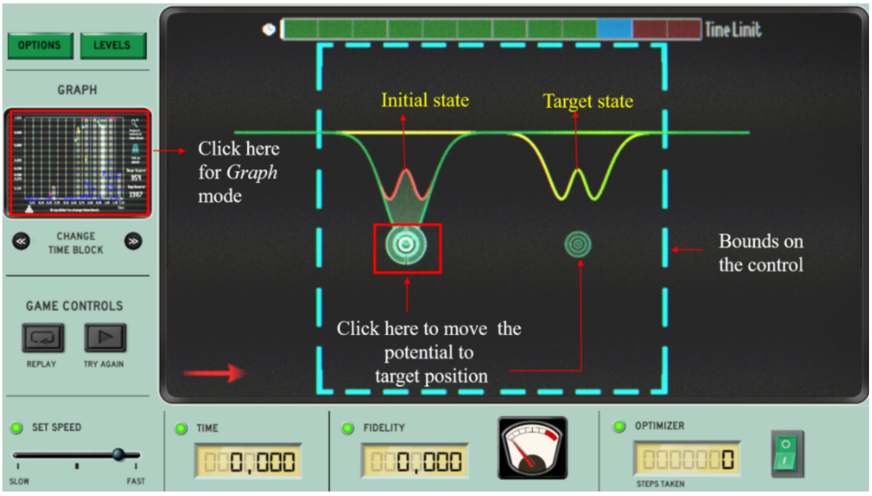



Figure 4.2: Screenshots from the game *Quantum Game* (previously named as *The Quantum Flytrap*). In *Quantum Game* the player solves puzzles introducing the basic actions and logic of quantum optics equipment.

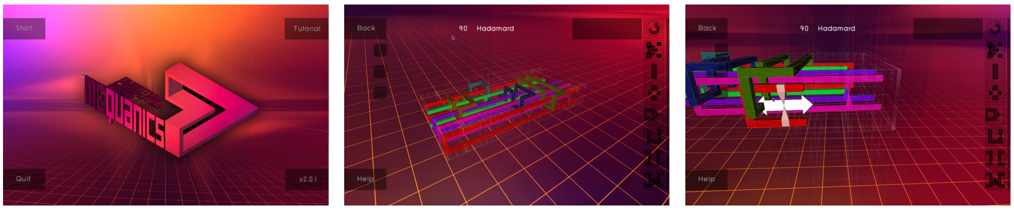
*Game* (previously named as *The Quantum Flytrap* proves as an excellent combination of gamified puzzles and numerical simulation of quantum physical phenomena (see Figure 4.2). The inspiration of educational games has further fostered the development of learning platforms that integrate quantum games with educational materials [35]–[37]. Various studies have proved animations, visualisation instruments, and interactive simulations efficient for learning purposes in quantum physics teaching [27], [28], [30]–[34], as well as in research settings, as exemplified by the Science at Home team's investigation of the visualisation and simulation tool *Quantum Composer* [128]. Turning numerical quantum simulations into interactive visual tools have also been created by, for example, the *Spin Drops* -project, which visualises quantum state evolution and entanglement in a way that concretises state polarisation useful for presenting, for example, NMR pulse effects on certain quantum systems [129], [130].

Academic actors within the study of quantum physical sciences have been inspired by the advantages games have brought for citizen science research. *Quantum Moves*, *Alice Challenge* -platform, and their successor *Quantum Moves 2* (see Figure 4.3a) are citizen science games, where players find solutions meant to optimise a certain quantum state-transfer process within the framework of quantum optimal control [15], [131], [132], [3], [133]–[136]. In *Quantum Moves 2*, for example, the player attempts to move a 2-dimensional graph with a well-shaped confinement inside which the visual quantum simulation sloshes accordingly in a water-like manner. The game aims to position this "quantum liquid" at a designated spot as fast as possible. The players were able to gain intuition upon the behaviour of the studied system and this *crowd-sourced heuristics* could be used in the further studies [11].

A game called *Bell's theorem* was designed test the fundamental theory of quantum information itself [17]. On November 30, 2016, the game was launched under




(a)



(b)

Figure 4.3: Screenshots from two quantum games: (a) an annotated interface of the Game mode in *Quantum Moves 2* (*Shaeema Zaman Ahmed* [11]), and (b) screenshots from *meQuanics*. In *Quantum Moves 2*, players manipulate a wave-like potential to control the movement of a liquid-like quantum object, aiming to guide it to a specific location. *meQuanics* offers puzzle-solving challenges with intricate knot-like structures. Both games, *Quantum Moves 2* and *meQuanics*, are citizen science games focused on exploring quantum physical sciences.

the event *The BIG Bell Quest* in order to generate human randomness for testing the Bell theorem in quantum information [137]. Players made binary choices to determine paths for their characters, producing bits sent to 13 experimental groups conducting various physical tests. Utilising a citizen science game, the experiment leveraged human-generated randomness to ensure the integrity of the test and demonstrate that quantum entanglement challenges the notion of local realism.

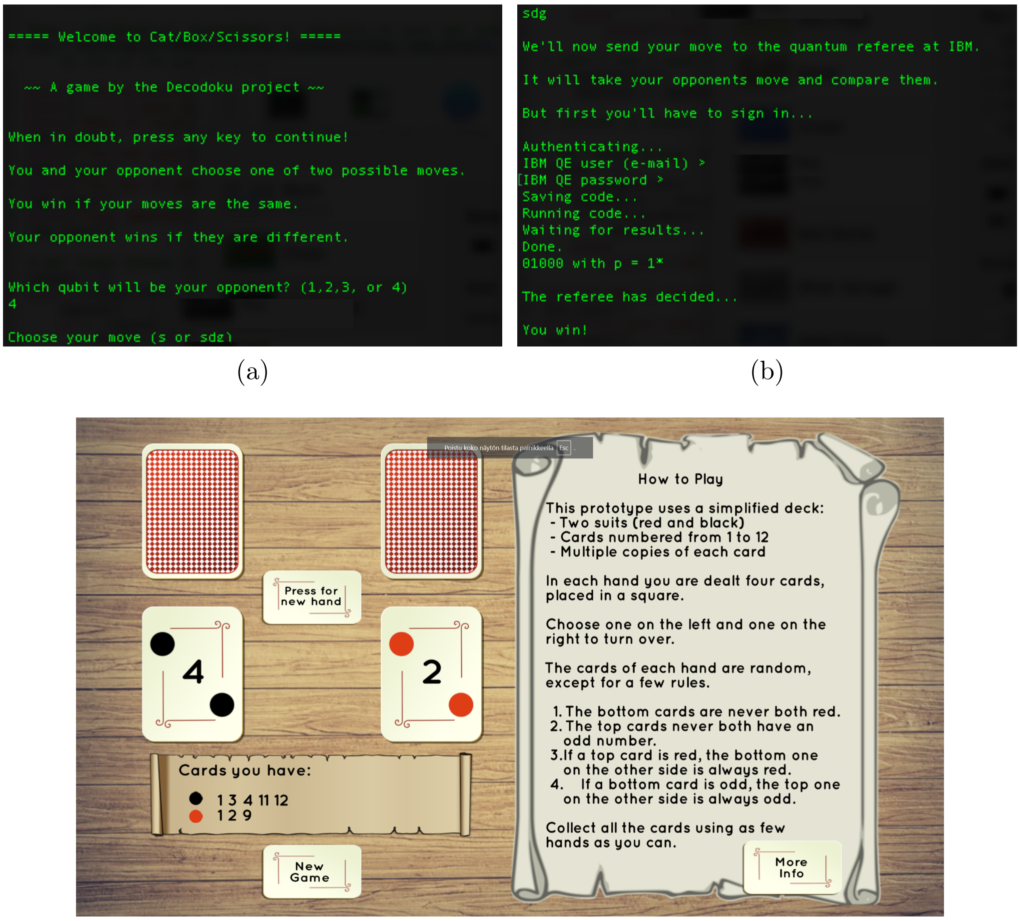
The game *meQuanics* was published in 2013 as a prototype citizen science game for optimising quantum algorithms (see Figure 4.3b) [16]. In *meQuanics* the aim is to reshape complex three-dimensional knot-like structures according to the rules given in the game. As players simplify complex knot-like structures, minimising their size according to game rules, they contribute to optimising quantum algorithms. Games have also been developed to allow the public to design methods for quantum error correction, through figuring out how to solve puzzles like in the game *Decodoku* [138]. Opened to the public in January 2016, the citizen science game aimed to demystify quantum physics and challenge preconceptions. Given that existing decoding methods were heuristic, the game sought to develop topological quantum error-correcting algorithms based on player solutions. It featured three versions and a tutorial mode to teach quantum error correction without requiring prior mathematical knowledge. Although the game did not collect data on player moves, players could discuss their solution methods on an open forum, leading to highly satisfactory results.

### 4.2.2 Games on Quantum Computers and Simulations

Shaping the early steps of quantum games towards something transformational was the open access to quantum computers for the public. In 2017 the first publicly accessible IBM Quantum device was accessible using the newly released system development kit, *the Project Q* and later the cloud-sourced access to different providers has opened up the exploration of quantum computers through games. The possibility to explore the limits of the early quantum computers drove for the development of the first *quantum computer games*, games on quantum computers [14]. IBM Quantum as well as Microsoft, have supported the development of quantum computer games by offering low-level and easy-to-approach tutorials for developing games and other programs on quantum computers in order to provide for a fruitful open-source development of quantum software [37], [139]–[141].

Similarly to the first digital games, the first games on quantum computers were adaptations of simple games that are known and played by many. This was to make it easier for the player and the developer to see and understand better what is different, when you have a quantum computer behind the game. *Cat/Box/Scissors*, inspired by *Rock-Paper-Scissors*, was born as the first game running on a quantum computer (see Figure 4.4) [142]). This game is essentially the classic *Rock-Paper-Scissors* against the quantum computer, which offers the possibility of a winning tactic over the noise-induced quantum-sourced randomness in the opponent's moves. The game was playable through the command line and was developed by a quantum physicists working at the research group behind IBM's quantum computers, which allowed them the direct access to the machinery.

The game essentially used the quantum computer as a random number generator, but as the developer was inspired to develop a game that would exemplify quantum physical phenomena in the game play, a little later a multiplayer game (for two players) called *Quantum Battleship* was developed. The game inspires from the Japanese version of the classic *Battleships*, where each ship is represented with a single position, but require a different number of hits to sink. On the game, the positions of the ships are chosen from five possibilities on a provided grid and the damage done on them is expressed in percentages. Each ship corresponds to a qubit on the processor and each strength of a ship corresponds to a different type




(c)

Figure 4.4: Screenshots from the games *Cat/Box/Scissors* and *Quantum Solitaire* by James Wootton. (a) At the start of the game the player chooses their opponent. (b) The game requires an identification to the cloud system for accessing the quantum computer. *Cat/Box/Scissors* is an adaptation of *Rock/Paper/Scissors* on quantum hardware. (c) *Quantum Solitaire* is a card game based on the game of *Solitaire*. The game connects to a quantum computer provided by IBM.

of quantum gate operated on that qubit, when it is chosen to be bombed. This corresponds with the number of hits the ship is sinkable with. The qubits used are entangled in pairs and in addition to that there is considerable noise in the processor, so the percentages indicating the damage of the ships are not always in line what is predicted by the theory for ideal qubits. For the players, exploring the effects of decoherence are used this way to build the gameplay. Both *Cat/Box/Scissors* and *Quantum Battleship* were ran through a command line interface and as there were not many quantum computers available, the users were required to wait a long processing time because of the long queues on the quantum computers.

A quantum computer is able to create certain types of data exhibiting quantum correlations before a gameplay. So by careful planning a quantum computer game can be developed in a way, that would not require long waiting times. Such planning is found behind the game *Quantum Solitaire*, an online card game based on the game *Solitaire*. The randomness exhibited in the shuffling of the cards is generated in a conventional way, but based on probabilities calculated on a quantum computer (see Figure 4.4c). In this game, your mission is to collect all the possible red and black cards from the deck using as few hands as possible. Here the player may use knowledge of quantum mechanics to draw conclusions on which combinations of flipping the cards up give the best probabilities of success.

These early quantum computer games had educational elements in them, mostly to educate about the early quantum computers and bring them front to greater audiences. *Quantum Battleships* used the time the players needs to wait for their turn at the quantum computer and for the processing time to educate about the basics of quantum computers and quantum computing. It did this through a narrative that continued during each turn that required a wait due to the processing time on the quantum computer. A quantum computing startup, called Rigetti released their quantum SDK in 2017 together with a game that demonstrated simple concepts of quantum computing, but the game is no longer to be found [142].

Educational games on quantum computing and related to quantum computers in general have been part of outreach attempts of quantum computer manufacturers like IBM and Google. In 2018 a two-player cooperative board game *Entanglion* was created at IBM Research to introduce basic quantum computing concepts [143]. The mobile game *Hello Quantum* was developed by a collaboration between IBM Quantum and the University of Basel for teaching the logic behind quantum computational operations through approachable puzzles and is still available for mobile [38]. IBM has also provided gamified learning materials on learning quantum computing for connecting to their online quantum computers through the IBM Q Experience using their Quantum Development Kit *Qiskit* [144]. Google released their game, *The Qubit Game* on the World Quantum Day in 2022 together with online learning materials designed for teachers to accompany the earlier released *Quantum Chess* [145]. The learning materials supporting the educational use of *Quantum Chess* were developed in collaboration between Caltech, Google, and the creator of *Quantum Chess*, Quantum Realm Games.

### 4.2.3 Quantum Game Jams and the Popularity of Quantum Games

Until 2014 quantum games were produced mostly by groups of quantum physicists and quantum computing experts [10]. That year the first *Quantum Game Jam* (QGJ) was organised and led to a series of 6 quantum themed game jam events that brought together people both from the quantum physics research side and the more professional game developer side [12]. Since 2017 the event included an additional aim to provide a base for the development of citizen science game prototypes, and for that a pre-designed numerical simulation tool was offered as an resource for the developers. This tool is presented in Chapter 6.

In 2019 the event was ran as an invite-only event for experienced (quantum) game jammers, indie developers and was organised together with IBM Research and IBM Quantum to provide mentoring and dedicated access to quantum computers. It was also the last QGJ to provide the numerical simulation for citizen science game prototype development. Since then, also other actors like the Indian community for Quantum Computing, *IndiQ*, and the international quantum computing association *QWorld* have organised game jams and hackathons with emphasis on the use of IBM's quantum SDK *Qiskit* [146].

Like most game jams and hackathons, also QGJs were forced to go online after the pandemic of 2020. The online QGJ has been organised on a yearly basis since 2021 through the collaboration of Aalto University, University of Turku, and IGDA Finland [13]. To date, several games have either been developed using quantum computing software such as *Qiskit* offered by IBM Quantum, or are even utilising a quantum computer. In addition to these short-term events, a series of quantum game courses was organised at the Aalto University between the years 2020 and 2022 [147], [148].

The development of a numerical simulation for the purpose of QGJs to work as creative ground for citizen science games has also lead to the development of commissioned artwork like the *Quantum Garden* and the VR-installation *Quantum Playground* more closely introduced in Chapter 6 [149], [150]. Furthermore, the development of quantum games has offered means for learning about quantum physics, quantum technologies, and quantum computing to the people creating these games.

CHAPTER 5:

# Methods

This chapter describes the methods used for gathering knowledge related to the principles for quantum game design from the design projects presented in Chapter 6. The analysis of the development processes for the multidisciplinary collaborative quantum game and quantum art projects described in this thesis is inspired by social-scientific autoethnographic methods.

The motivation for using the presented methods stem from the desire to understand how social and cultural aspects related to the fields of expertise of the project participants present themselves in the studied context and possibly shape the observations. Autoethnography refers to the study of self and the combination of personal experiences with the surrounding culture [151, p. 154]. The relevance here is that this study examines quantum game development through personal perspectives on the processes. The methodology described in this chapter aligns with practice-based research within the domain of design research. It involves integrating practice and research, collecting design artefacts, describing design processes and decision-making, and creating guidelines based on active participation and analysis of the projects.

The methods or practice-based research involve the use of design diaries, self-observational memos, and notes written during meetings with the development teams [152]–[156]. Specifically, the chosen methods have been inspired by the *Research through Design* (RtD) approach, which has led to the descriptions of the projects presented in Chapter 6. The RtD method is an approach where design practice and the creation of artefacts are used as a means to generate new knowledge and insights. These reports are supported with selected visual materials gained throughout the development processes. Unless stated otherwise, the observations presented in this thesis reflect the author's interpretations.

In order to differentiate the analysis from an *auto*biography, which concentrates on conveying one's personal experiences [157], [158], the online conversations between members of the development team have been revisited. These conversations have been recovered through emails or messaging programs like Slack, and Discord[1], to gain supplementary insight into the design choices in the development processes and the communication between disciplines. Part of these conversations has been gathered into separate digital documents for the purposes of this study. Discussions that had no direct relevance to the presented projects or resources related were discarded from this study. The amount of discarded discussions between different project team members varied and by themselves impart some information about the relations between these members. A deeper analysis into the intricacies of social relations was not within the scope of this study.

For gathering the project descriptions of Chapter 6, the text-based materials, such as meeting notes, personal notes and the mentioned online conversations related to these projects, have been categorised based on their relevance to the study and to the design phases observed in the projects. The relevant hand-written notes were transcribed to digital notes. This has allowed the use of document annotation functionalities (like comments), file headings and section headings, and colourful highlights. The projects have partly overlapped and intertwined and therefore the materials required categorisation based on specific projects. In addition, explanatory labelling on the relations to different design phases has been used for this purpose both on the text-based materials as well as visual materials. These annotations were used to highlight aspects like critical design phases, design decisions and relations to

[1]Slack and Discord are cloud-based communication platforms designed for teams and communities, providing real-time messaging. They enable the creation of channels for focused discussions and file sharing, enhancing team productivity and communication efficiency. In addition to this, Discord allows voice and video channels. With its adjustable servers and features, Discord serves as a hub for community engagement and group discussions and is widely used by gaming communities.

specific projects. With colours, themes related to design decisions, design revisions, communication, and resources were possible to differentiate with different colours. Additionally, pictures, videos, and earlier versions of project files have been collected, revisited and added to these text-based memos to provide additional context and insights.

The interpretation and classification of materials have been done in an iterative manner of going through the project materials and reflecting them upon the knowledge gained from other quantum game projects. Through the iterative process, annotation allowed structuring and organising the materials with descriptive comments, reflections, and interpretation. The iterative process of carefully reviewing the materials is a method supported by practices of individual and collaborative autoethnography [154]. Through this iterative process, patterns (in form of critical development phases and practices) in the design processes have emerged. These patterns have guided the form of project descriptions of Chapter 6 and lead to the guidelines gathered in Chapter 8. Annotation presents itself in this thesis as video snapshots, pictures, and figure captions of selected materials. In the following we further motivate the chosen methodologies and mirror their usage in the presented study.

## 5.1 Research through Design in Quantum Game Development

Research through design (RtD) is a methodology where the researcher actively participates in the design process instead of merely observing the process or the outcome. The primary objective of the RtD methodology is to enhance design methodologies [159]. This methodology reveals information about the preferred state of the design process, meaning that it contributes to the understanding of why and how the process is as it is. The author has been integrated into the presented projects, coming from two professional backgrounds: game development and quantum physics research. This integration has allowed for meaningful inclusion of all aspects related to quantum game design. By being involved in active design and creation, it has been possible to observe the development of quantum games from a perspective greater than what could have been gained through mere observations and interviews.

In RtD, there are different stages: coupling, interweaving, and decoupling [160]. Coupling represents the state of the RtD process where research and design interests are united. This phase provides the basic frame and constraints of the project so that it serves both these levels of interest. For the presented projects, this phase represents the first involvement of the author in the QBB project. At that stage, there was not yet a foundation for the research surrounding the design methodologies of projects using the QBB. The project primarily aimed to assess the usability and functionality of the QBB by making it available to participants of the Quantum Game Jam (QGJ) event (see Section 6.1). This phase led to the development of quantum games demonstrating the use of QBB and provided a possibility to study the concept of the quantum game design process and development. Therefore the scope of the RtD study eventually extended beyond the QBB-related projects. This provided a larger framework for the study, as with the involvement of other quantum game development processes, the author was able to study quantum game development from a wider perspective.

The interweaving phase of the RtD study denotes the stage where research interests and design interests mutually influence each other. At this phase, the project processes, methods, and validation are established. This phase covered the entire duration of the design and development process for the presented projects as it touches the very research questions of this study. As at the time of these projects no general guidelines for quantum game design existed, this phase was about comparing the projects unfolding to each other, Quantum Game Jam development processes, and to game development or software development in general. The methodological aspects of RtD focus on *how* to gather the necessary data. For the purpose of creating project descriptions, it was decided that any observations and insights gained during the design process would be gathered. Design diaries, meeting notes, discussions between project members, and screen captures of the design phases were gathered as the main method for data collection, whereas the validation of the design processes was a dynamic learning process that extended from the beginning of the project involvement to the writing of this thesis.

The decoupling phase represents the final stage of an RtD study. At this phase, the focus is fixed either on the design or the research. For the presented projects, decoupling meant concentrating on the production firstly as a designer and then concentrating on the gathered data as a researcher for this thesis. RtD focuses on acquiring knowledge and an understanding of the development process rather than solely focusing on the product or art piece itself, which makes it suitable for studying the design of quantum games. The analysis of the gathered materials and the writing of this thesis can then be considered the concluding phase of the decoupling process. In this phase, the descriptions of the design processes were collated in a comparative composition to provide a more comprehensive understanding through their comparison.

## 5.2 Annotation and Coding of Materials

Annotated portfolios are an established method of RtD, where the annotations bring together designed artefacts as a systematic body of work [161], [162]. In an annotated portfolio, the product and the design process behind it are presented through materials with added explanatory or descriptive comments. In the projects presented in this thesis, the studied materials used for the formation of Chapter6 have typically been meeting notes, design diaries, online discussions, and supplementary visual aids such as screenshots taken from the different versions of the designed games, with the main emphasis on design diaries. From these materials, a selection of process screenshots, video snapshots, and other visual materials were chosen to be included in the portfolios of Chapter6. These portfolios mainly comprise project descriptions and figures with captions, but it should be noted that, in general, annotated portfolios can be presented in a multitude of ways, even as videos, stage shows, or exhibitions collating pieces that may otherwise be seen as unrelated [161].

Annotated portfolios are an important form of information upon which future design processes can be built. They bring "means for capturing the family resemblances that exist in a collection of artefacts, simultaneously respecting the particularity of specific designs and engaging with broader concerns" [162]. It is also stated that design requires annotation to make clear and accountable contributions to research [161]. Although theories of what kinds of products should exist and how they should be designed are important, creators often turn to concrete examples of other work to gain inspiration and direction [163]. Specific examples of practice allow for discussion on the relevance of the examples to specific needs, thus allowing room for the beginning of conscious design thinking.

Analysing design diaries and other data related to a design project for research includes several steps of categorisation, coding, and annotation in an iterative manner. Coding of text-based materials refers to strategies of organising data, developing analytical structures for interpretation and representation, and building themes connecting empirical findings with broader literature [164], [165]. To reveal meaningful information behind possible patterns and categories, it is guided to examine conditions within the setting, interaction among the actors, used strategies and tactics, and consequences in a structured manner. For the extent of this thesis and considering the amount of materials related to the presented projects, it was decided to focus on a more straightforward adaptation of the coding process by not engrossing into formal categorisation of the materials. The materials were reviewed in an iterative manner, but not every word or sentence was made to fit into a category. Instead, emphasis was on aspects that affected and led to design decisions and suited different phases of game development cycles. For this purpose, initial categories were designed by referencing the phases in the Scrum framework and the structure of quantum physics-themed game jam events [13]. Through the iteration of the materials, the aspects were fitted to these phases with an aim to find anything particular in these design processes that might not fit a general type of game design framework. This coding procedure was then adjusted to better orient towards what was found related to the phases of development and design. Such possible aspects were to be gathered as separate categories, then provoked by later iterations.

## 5.3 Advantages and Limitations

RtD has been discussed and used in the field of human-computer interaction research and practice, where products and concepts of design provide valuable and topical opportunities for insight, reflection, and innovation [161]. Such an approach acknowledges and embraces professional practice's contributions to knowledge. This aspect makes the approach particularly attractive for this study as quantum game design combines the special expertise of quantum physicists and game designers. Annotating entries in a portfolio adds depth and context to the materials, facilitating the analysis and interpretation of the design diaries. This process allowed the identification of what was particular in these design processes, and the gathered knowledge about the design and development process of quantum games was then transformed into the guidelines for quantum game development practices in Chapter

8. This process helped draw meaningful insights and establish connections between the entries, research objectives, and theoretical frameworks, ultimately contributing to the overall findings and conclusions of the study.

For the presented projects, the individual tasks were not rigorously documented separately from documentation of discussions and meeting notes. Instead, they centre on the tasks and responsibilities of the author, primarily consisting of personal notes. However, it should be emphasised that the aim of this thesis is not to underrate or minimise anyone's individual views or input. On the contrary, it would have been particularly fruitful to collaborate with other team members from these projects in a collaborative autoethnography to possibly provide a more insightful view of quantum game development [154]. Yet, for the presented projects, none of the other team members were present in all of the projects, nor was it possible to carry out interviews within the scope of this thesis.

The scope and methodologies of this study could have been chosen from a different perspective. The research process in this study could be viewed as a form of "Research *for* Design". Supporting this is the fact that the author has also acted as both a viewer and a participant, as they are not the sole designer and developer of all the presented projects. The practices of the involved designers, including other physicists, are also treated as the object of the study. However, since the study does not involve interviews or questionnaires with these practitioners, the used methodology would not serve as a suitable representation of Research for Design.

Similarly, the approach employed here can also be seen as a form of "Research *into* Design", as a part of the thesis, a review is conducted on the history and landscape of quantum games (see Chapter 4). Research into Design involves documenting objects, phenomenon and the history behind them. What sets RtD apart from these other approaches is the focus on the process and the perspective of viewing creation as part of the research process. Although the study could have benefited from additional RfD methodologies, the extent of this thesis has imposed its limitations. It has been a deliberate decision to avoid formal coding of data entries when categorising them. Specifically, no qualitative data analysis tools have been used in the study. The data entries (design diaries, meeting notes etc.) were manually organised and annotated by incorporating explanations, reflections, and interpretations.

Novel products alone or even as a repertory are not always seen to be sufficient enough to count as research, which further promoted the use of RtD methods [161], [162]. The challenge has been in finding the balance of rigorous methodological frameworks and the possibilities for designers to take inspiration from unorthodox sources or invent *ad hoc* approaches. Also supporting the choice of RtD is the fact that the author was either the main designer or part of the design team in each project is supported by Bowers [162]. He suggests the use of many artefacts either from a single studio or designer in RtD [162].

The core of design is multidimensional, situated and lies within the relations the situation has with its surroundings. Trying to fit the process into general guidelines may provoke the very nature of design, which presents as a challenge for structuring the Chapter 8. Thus, by providing the structured process descriptions that have supported the creation of design guidelines allows room for critical reflections.
An additional study would have been centred on the usage of these games instead of their design processes. For quantum games, comparative data, general practices and values of evaluation does not yet exist. Instead, the focus here has been on the reflections of the author's views on what has been critical for the development of the presented games, but also on what is salient for research in interaction design. Studies on theories related to interaction design and game design have allowed for articulation of aspects of the design, but the results, in the form of quantum game

development guidelines, heavily structure the particular design processes evaluated in this thesis. These guidelines present values the author wants to promote in future quantum game design. These values stem from both experience and an extensive literature review on subjects related to quantum mechanics, game design, serious games and pedagogy.

Overall, these methods of autoethnography, though still debated and critiqued [151], [157], [158], [166], [167], were well-suited for the purpose of analysing the presented projects. Though there are yet not too many scientific papers discussing the design process of quantum games and quantum art [12], [117], the amount and multitude of such projects already embody a large community of game developers and artists [10], [12]. It is therefore relevant to provide descriptions and personal insight on the procedures and methods present in the field of quantum games and quantum art. As there were no further resources to rigorously test the citizen science or the educational aspects of the games, the design process offers the most valuable insight for future projects, in particular in the field of quantum game development.

To conclude, RtD is an approach to scientific inquiry that specifically leverages the unique insights obtained through design practices. The project descriptions in Chapter 6 provide essential context, as it is crucial for building the rationale for the selection of design guidelines in Chapter 8 to support significant advancements in the field of quantum game design and to lay the foundation for further research on the subject. To support the further development of quantum game design culture (or science game design in general), the field requires open documentation and description that allows the community to leverage the knowledge derived from the process. This thesis therefore provides valuable insights gained through composing an annotated portfolio from a multitude of design processes, culminating in the formulation of general guidelines for quantum game development in Chapter 8. Design theory is emergent [163], and so are the first steps of studying the design of quantum games.

CHAPTER 6:

# Projects Exploring Quantum Physics through Games and Playful Art

In this chapter, five projects surrounding the creation of quantum games and playful art are presented. Common in all the presented projects is the use of numerical simulations related to quantum physics. In addition to the project descriptions of these five artefacts, the development of a numerical simulation tool for the purpose of citizen science is described as it facilitated the development of four of these projects. For two of these artefacts, another numerical simulation was written for educational and outreach purposes and is described alongside the project descriptions. The order of which the five projects are introduced in highlights their purpose and the simulations on which they are based (see Table 6). These projects have not only progressed concurrently but have also influenced and even spawned each other.

The first game, *Hamsterwave* was created during a Quantum Game Jam event, called *Quantum Wheel*, that was organised for the creation of citizen science game prototypes in 2019 [12]. The prototypes developed at *Quantum Wheel* laid the groundwork for the subsequent development of *QWiz*, a citizen science game. The citizen science game prototype *Lemminqs Condensate* is a solo projects created during a later quantum physics themed game jam. The quantum physic related interactive art pieces *Quantum Garden* and *Quantum Playground* were designed mainly for outreach purposes. The first version of *Quantum Garden*, and the games *Hamsterwave*, *QWiz*, and *Lemminqs Condensate* featured the same numerical simulation, which was updated to another in the sequential versions of *Quantum Garden*. This simulation was considered more suitable for visual representation of quantum phenomena for outreach educational purposes. *Quantum Playground* is essentially a virtual reality (VR) adaptation of that simulation.

An important background project that laid the groundwork, provided design constraints, and facilitated several of the projects discussed in this thesis is the development of the *Quantum Black Box* (QBB), which is presented in the following section. The development team behind the QBB has remained consistent dur-

Table 6.1: A listing of the projects presented in this chapter paired with information about the year they have been published, the connection to numerical simulations and the purpose that has set the design frame for the project. The numerical simulation *Quantum Black Box* (QBB) described a simple Bose-Einstein condensate and the numerical simulation of a 2D *Quantum Walker* (QW) simulates the evolution of a quantum excitation on a network. *: The simulation on *Quantum Garden* was updated from QBB to QW 09/2019.

| **Name** | **Years** | **Numerical simulation** | **Purpose** |
|---|---|---|---|
| Hamsterwave | 02/2019 | QBB | Citizen Science |
| QWiz | 05/2019 - 10/2020 | QBB | Citizen Science |
| Lemminqs Condensate | 08/2021 | QBB | Citizen Science |
| Quantum Garden | 09/2018 - 02/2020 | QBB*, QW | Citizen Science, Outreach |
| Quantum Playground | 04/2020 - 11/2020 | QW | Education Outreach |

ing my involvement, comprising a theoretical physics professor, two postdoctoral researchers, and two doctoral candidates studying open quantum systems at the University of Turku. A recent doctorate from the same research group had been involved in the project before me joining. Them and one of the postdoctoral researchers provided me with valuable insight and knowledge on the overall project as well as the physics involved. Based on statements from other team members, these two people were the key contributors in studying the research problems related to the QBB.

The entire team behind QBB has not been actively involved in all the projects examined in this paper. For instance, the puzzle game *Hamsterwave* in Section 6.2 was initially developed at the Quantum Game Jam 2019 and subsequently further developed by two original team members from the event team and myself. During the event, another physicist from the QBB team provided consultation. The *Lemmings*-inspired game *The Lemminqs Condensate*, presented in Section 6.4, was solely developed by me, without further consultation from additional experts. Detailed information about the individuals involved in each project is provided in their respective sections.

With the introduction of a second iteration of the interactive art installation *Quantum Garden* in Section 6.5, the focus of the presented projects shifted from the QBB to the theory of quantum walkers, a quantum physical analogue of *random walkers* [168]–[170]. During this shift one of the postdoctoral researchers was naturally replaced by another, whose research was more concordant with the study of quantum walkers. This shift further led to the development of *Quantum Playground*, as presented in Section 6.6.

In the following, the projects are presented by first introducing the artefact, design constraints and then presenting the development team, and the development process. For each game, project reflections are presented separately and general reflections are presented at the end of the chapter.

## 6.1 The Quantum Black Box Simulation Tool

The *Quantum Black Box* (QBB) was created as the first step for facilitating systematic research on complex numerical quantum physics problems with citizen science games. The primary motivation behind the development of QBB was to provide game developers with a ready piece of code allowing them to incorporate a numerical simulation of a quantum physical system into games in a straightforward manner. It started as a `Python`-based interface developed in 2017 by researchers from the Turku Quantum Technology (TQT) group, with Dr. Nicola Lo Gullo and Dr. Matteo Rossi as the lead programmers and Dr. (later Professor) Sabrina Maniscalco as the project lead [171]. The QBB project has throughout its development in addition credited those members from TQT who have been involved in the development of QBB and applications it has been incorporated into, including Dr.

Francesco Cosco, Dr. Walter Talarico, Dr. Boris Sokolov[1]. I joined the progress of QBB in late 2018, when some of the original members had already shifted to other endeavours.

The incorporation of QBB in games aimed to develop engaging games that would allow players to act as citizen scientists and find potential solutions to an optimisation control problem associated with Bose-Einstein condensates, These are sparse gases of specific types of particles that are cooled down to extremely low temperatures, which then allows them to form a controllable quantum mechanical system. The study of Bose-Einstein condensates is closely linked to the engineering of memory-control units for quantum computers. It involves distinguishing between two distinct quantum states of these condensates and optimising their control to enable information processing in quantum bits (qubits) [172].

For the presented projects QBB was a simple numerical simulation of a time-dependent Schrödinger equation for a one-dimensional particle system trapped in a triple-well shaped external potential. The external field may represent the actions of lasers on atomic gasses, most commonly consisting of Rubidium-87. Other choices for the potential would be a piecewise definition, and was to be explored in the future. The controls of QBB are the vertical positions of the leftmost and the rightmost wells of the confining potential, thus controlling the relative distances of the wells (see Figure 6.1). Based on these values the simulation outputs a graph representing the probability distribution of the gas-system within the potential and calculates a score based on the population of the rightmost well. This score is the average over the population of the rightmost well at the end of the simulation round. In addition, the simulation provides a score between 0 and 1 on how close the state of the system is to the desired state (1) and numbers representing population on the

[1]These people were in the middle of their doctoral studies during most of their involvement in the QBB project but have since graduated with doctorates.

leftmost and the rightmost wells.

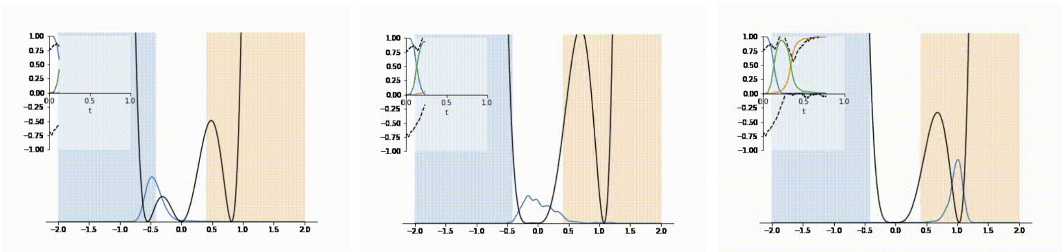
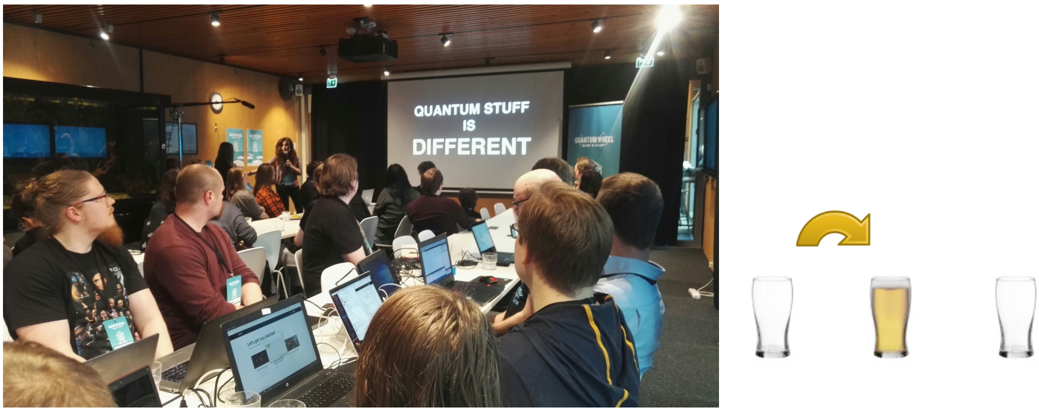


Figure 6.1: QBB triple-well, a confining potential consisting of three separate harmonic wells, whose leftmost and rightmost well are the controls of the simulation. Three frames from the example simulation of the QBB system. On the upper left the picture shows the respective positions of the leftmost and the rightmost well with respective to time as dashed lines with the average position of the condensate in blue. The bigger picture shows the probability distribution of the condensate with blue, while the triple-wells are drawn in black.

For verifying the suitability of a game to provide optimal solutions, the chosen strategy was to develop a version of the problem that has at least one known optimal strategy. If this solution would be obtainable through the gameplay, it was considered as a verification of the game's suitability to work as a citizen science game. The version of the QBB used in the project presented in this chapter has a known solution achievable through a machine learning algorithm developed by Dr. Matteo Rossi. This algorithm is designed for systems where the interactions between the particles of the studied gas are zero. The next phase was intended to incorporate a model for strongly interacting gases.

QBB was initially introduced at the Quantum Game Jam of 2017 and continued to be part of this annual event until 2019 [12]. QBB was introduced to game developers together with an introduction on how it is supposed to be used and what type of a problem it simulates. The introduction was usually given as a short talk by one of the researchers (see Figure 6.2). Since 2020, these events have been organised online without the involvement of the QBB project [13]. Game jams impose time restric-




(a) (b)

Figure 6.2: (a) A picture from the Quantum Game Jam of 2019 called the *Quantum Wheel*. The professor is presenting the QBB simulation and its purpose for the participants on the first day of the event. (b) The procedure related to the QBB simulation tool was presented using a classical analogue of transporting a liquid from a glass to another, where the order of the glasses could not be changed.

tions on the development process, emphasising the importance of providing QBB to the developers in a way that is easily deployed. In early 2019, the team behind QBB partnered with the game development company *MiTale* to involve professionals from the game development industry in the QBB team. This collaboration enabled further development of QBB as a Unity wrap-up, which was presented to participants at the 2019 Quantum Game Jam. Additionally, an example Unity project utilising QBB was provided. Half of the games developed during the 2019 Quantum Game Jam incorporated QBB into their design [12], [173]. Notably, a game created at the jam called *Quantum Fruit*, offered a gameplay experience that allowed some experienced players to reach the known solution, even though the quantum experts themselves were unable to fully master the game (see Figure 6.3a).

Although *Quantum Fruit* was not further developed after the event, it served as a proof of concept for the team behind QBB which allowed the continuation of the QBB development. The insights gained from the games created during the jam,


(a) (b)

Figure 6.3: Screenshots from two games developed at the Quantum Game Jam 2019, *Quantum Wheel*, that used the QBB simulation [173]. (a) *Quantum Fruit* is a game where the player uses a special ejecting machine for throwing fruits and berries to a big jam jar. The player adjust variables for the throw and based on them, QBB provides values that determines the trajectory. (b) In *QSpell* the player has control of the hands of a wizard and the movement of the hands are transferred for QBB, which then determines the size of a wheel on the screen. The aim is to grow this wheel.

particularly the concept behind a game called *QSpell* (see Figure 6.3b), inspired the development of *QWiz*, a citizen science game prototype created in collaboration with MiTale. *QWiz* was subsequently integrated into an online learning platform for quantum physics [36]. During the final active months of the QBB project, the development efforts were primarily focused on the *QWiz* game prototype, as discussed in Section 6.3.

### 6.1.1 QBB Project Reflections

In the beginning of my involvement, the documentation and knowledge related to the workings of the initial version of QBB was scattered and I received no proper onboarding to the project, which led to some initial confusion and misunderstandings between me and the team related to the workings and aim of the QBB simulation tool. I was instead left to seek information from project members, who each had only fragments of the information and were guiding me further to others. This is understandable, as the research group was evolving and the project was managed on the side of research work, so part of existing documentations were either lost of forgotten with prior team members. Gathering this information in order to form a comprehensive project documentation did challenge time resources, but possibly offered a more in-depth understanding of the project state than I would have gotten from a readily polished documentation. It still denotes the importance of project documentation and on-boarding of new members.

Some of the information transfer and communication may have suffered from design discussions held privately between a limited number of the research members involved, which were then not efficiently communicated to the rest of the team. Partly such discussions were inadvertently made in exclusion of part of the members, possibly due to confusion with the number of different communication channels the group had active at the time.

Quantum Game Jams between 2017 and 2019 provided valuable insight for the development of the QBB as the events were exposing QBB to various types of project uses. Something distinctive for a science game jam like the Quantum Game Jams has been short lectures explaining basic concepts of quantum physics [12]. In addition to this, simulation tools like the QBB have been separately described in an introductory manner. Visual representations used in these presentations were subsequently used to aid the communication between the team members at the event. Still, such fast, short lectures have not always been considered to be easily digestible [12]. This underlines the need to simplify initial briefings and focus explaining main functionalities of simulation tools or technologies presented to new, inexperienced team members in the beginning of the involvement. For a project with more relaxed time constraints, the discussion on the workings of the provided tools may extend deeper, but for science game jams special care and attention should be paid to match the level of difficulty to a short introduction and concentrate on what the main ideas are that need to be communicated.

For the QBB, in particular, it was important to describe the parameters the simulation is controlled by and what the return values are about. In addition to this, it was important to explain what was the particular value to be maximised through the procedure implemented in the game. This was not always included to the event presentations, but came about once the developers were introducing themselves to the tool and were guided by the QBB team members. Explaining the workings of the QBB, drawings of the confining potential in the problem and the wave-like form of the probability density describing the population of these wells were used. For this, an analogue was used of transporting liquid from one glass to another, where a glass could be emptied only to a glass right next to it (see Figure 6.2). This analogue helped draw attention to the differences between the classical counterpart of glasses and the quantum physical counterpart evolving despite moving any glasses and *tunnelling* though the well potentials. These visualisations were introduced in the opening lectures of Quantum Game Jams, but they were also observed to be used for communication between the physicists and other team members.

Another very valuable lesson from Quantum Game Jams between 2014 and 2019 was, that for avoiding as many technical difficulties as possible, a ready-made Unity integration was of greatest importance. Then again, this of course served only the Unity developers. The organisers of game jams are not usually able to avoid technical challenges with personal technological equipment of the participants. More so, it is important to make sure on many platforms that the code works, is easily integratable to a game and that there is help available when needed either for the installation procedure or for the usage. It became clear that instructions for installing the compatible version of Python and QBB itself should be easily available for different platforms. The development of the Unity integration in 2019 led also to the base mechanics of project *QWiz*, introduced in section 6.3.

In addition to the Unity integration itself, an example Unity project with simple mechanics combined with the QBB was presented for Quantum Game Jam participants in 2019. This example project proved valuable for many Quantum Game Jam 2019 event participants as it provided a concrete starting point for a project aiming to use the numeric provided by the QBB. In addition, the example project allowed for a playful introduction to the functionalities of QBB. Later a cloud-server based system for calling the QBB was developed for the project *QWiz*. Such a multi-user server based system could make incorporating QBB to game projects more straightforward and could therefore offer considerable advantage to bringing the QBB back to Quantum Game Jam events.

## 6.2 Hamsterwave

*Hamsterwave* is a puzzle game featuring a small hamster floating on ocean waves inside a hamster wheel, attempting to evade a pursuing shark (see Figure 6.4). The player controls the shape of a dynamic ocean wave on which the hamster rides. The objective is to guide the hamster to an island located on the right-hand side of the screen. The game is developed using Unity and is compatible with PC.

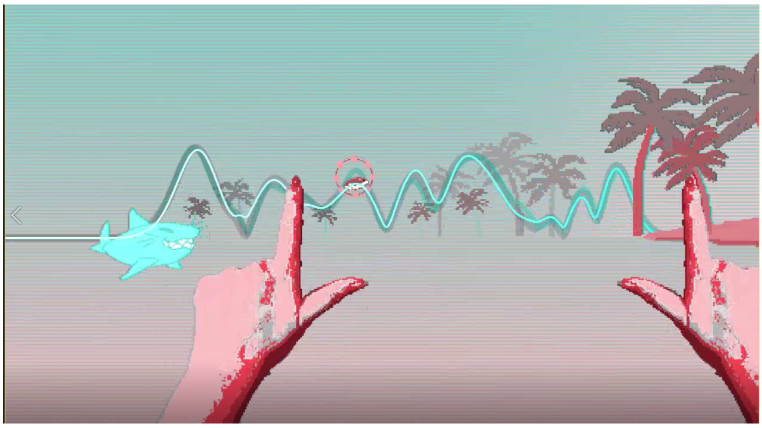
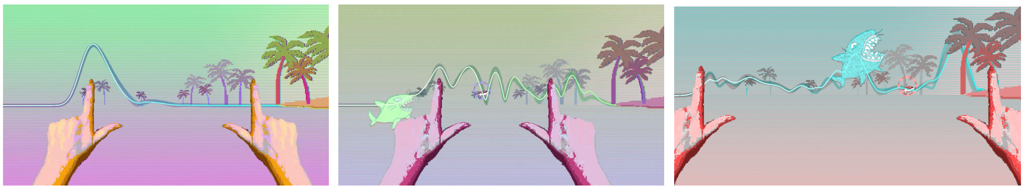


Figure 6.4: *Hamsterwave* is a game, where you battle against time to save a little hamster from an approaching shark by controlling a dynamical wave.

Hamsterwave was developed at the Quantum Game Jam 2019 as a citizen science game prototype and was later further developed to be exhibited at a game exhibition at the Helsinki City Library *Oodi* in 2020 [174]. The shape of the wave the hamster sails on derived from the shape of the plotted wave probability distribution simulated by the QBB. The design includes an island on the right-hand side meant to motivate the player to guide the hamster there. The stationary position of this island was also meant to motivate towards pulling the positions of the wells far from each other at the end of the procedure. The positions of the leftmost and rightmost potential wells of the simulation are represented by two hands visible on the screen. To support finding an (optimal) solution to the underlying QBB simulation quickly, a time limit was implemented in the game in the form of a shark approaching and chasing the hamster from the left-hand side of the screen (see Figure 6.5).



(a) (b) (c)

Figure 6.5: Three sequential frames from the citizen science game prototype *Hamsterwave*, that incorporates QBB in the game as the shape of the wave a little hamster sails on. The simulation is controlled by moving the hands. (a) In the beginning the wave starts from the position of the left hand. (b) The hamster sails on top of the wave and a shark character is introduced as a form of motivation towards helping the hamster on the island on the right. (c) After a set time the shark reaches the right-hand side of the screen.

### 6.2.1 Team

The original pitch that brought the team together was proposed by a rewarded indie game designer Sun Park and involved the concept of frames moving at different paces. The presentation involving two people expressing movement relative to each other was particularly captivating. This interesting and complex idea inspired two other experienced developers, Björn Lindholm and Sebastian Laitilta, and two quantum physicists, Igor Sokolov and me, to join in the brainstorming process. However, I was the only one familiar with the QBB. An experienced game artist Julia Rässa joined the team to create exceptional artwork for the game on the second day of the event after the development had started. The sound effects were outsourced to the children of Sebastian Laitila, and the music was provided by an experienced game musician, Elie Abraham, who was attending the event. Everyone, with the exception of the children, are presented in Figure 6.6 taken at the Quantum Game

Jam of 2019, *Quantum Wheel*.

In the development process of *Hamsterwave*, I actively participated in the brainstorming and game design phases where the basic concept and the idea of the games was developed. During the development phase from the second event day forward, my participation was limited to be a consultant on the usage of the QBB as I also served as one of the organisers of the Quantum Game Jam 2019. Technical issues related to incorporating the Unity extension of QBB into the game project were addressed by consulting the lead developer of QBB. Still, my active participation in the brainstorming and early game design phases during the event played a critical role in introducing the QBB based wave shape for the game.

Figure 6.6: The team behind the development of the citizen science game prototype *Hamsterwave* at the Quantum Game Jam of 2019 called *Quantum Wheel*.

### 6.2.2 The Design Process

The theme of the game jam was "Noise in the wheel," and one of the constraints was to incorporate the QBB into the game. During the brainstorming, it became evident that the team members were motivated to include QBB in the game, but the original idea of the moving frames did not easily support this design decision. The idea of a wheel led to the concept of a hamster and a hamster wheel being integrated into the moving frames idea. As time was running out for initial brainstorming, a decision was made to focus on the hamster and discard the idea of the moving frames which initially brought the team together. It was agreed that QBB could be used to draw a wave pattern for ocean waves on which the hamster could surf on with a surfboard. The board was later changed to a hamster wheel to suit the theme of the event.

During the game jam, an initial proof of concept demonstrating the base mechanics was created, but it did not meet the requirements of a citizen science game: The winning condition of the game was not tied to the localisation of the wave to the right-hand side of the screen, which would have coincided with the objective of the problem QBB is simulating. Instead, the winning condition was linked to the position of the hamster, which was not connected to the population of the right potential well. The hamster's rigid body was designed to bounce on top of the simulated wave. As a result, it was more beneficial to build the wave as a slope with higher waves on the left-hand side during the gameplay, limiting the population of the right-hand side.

Nevertheless, the game had functional mechanics and attracted players, garnering positive feedback from other event participants. *Hamsterwave* turned out to be an approachable and engaging game, generating significant interest from visitors during the showcase exhibition at the end of the jam. A lot of it was credited to the visuals and sound world of the game by the exhibition visitors and organisers.

After Quantum Game Jam 2019, *Hamsterwave* caught the attention of an exhibition organiser, and it was decided to be further developed the game for exhibition purposes. One of the organisers of the game jam event curated the further development of *Hamsterwave* and one of the original game developers of *Hamsterwave*, Björn Lindholm, was hired to implement the necessary changes. The necessary visuals for a menu screen, that would guide the exhibition visitors towards the gameplay, were ordered from the original visual artist, Julia Rässa. To serve the exhibition as an attractive artefact even when it is not played, the game was developed to incorporate an idle mode, which would show the game being played. As a secondary objective, it was agreed that the developer would also redesign the connection between QBB and the game, with my assistance. The goal was to modify the gameplay so that the player's main objective would be to optimise solutions for the underlying problem related to QBB. The idea and the overall concept of the game were not intended to be changed.

Figure 6.7: *Hamsterwave* being played at the end of the Quantum Game Jam of 2019 called *Quantum Wheel*.

As it was, installing *Hamsterwave* required the download and installation of `Python` and QBB. In addition, QBB required a specific version of `Python`, which made the overall installation procedure more complicated. The aim of *Hamsterwave* was to develop it into a self-contained game that could be showcased at events without this extra work. For this, the project received funding for a limited number of hours, primarily focused on redesigning the game and developing additional graphics for menus. Separate resources to ensure the active participation of a physics consultant were not available, and this interaction was instead left to rely on the personal investment of the team members. An attempt was made to find a way to connect the position of the hamster to the maximum of the wave plot, but no suitable averaging was found that would not scatter the hamster's transitions too much for the viewer. There were not enough resources available to address the interplay between the rigid body of the hamster and the wave in a visually intuitive manner while ensuring the hamster's position conveyed information about the population of the right-hand side well.

### 6.2.3 Project Reflections

Overall, *Hamsterwave* was a successful game in terms of being an attractive artefact, supporting playfulness, and maintaining the interest of the players. The team contributed to the evolution process of the game design in a supportive manner and the collaboration between the team members was respectful and positive.

The initial idea of a surfboard was changed to a hamster wheel to better align with the theme of the jam, "Noise in the Wheel". This is visualised with a reference to the event logo of the Ferris wheel that was accessible during the event [12]. Reflecting on this decision, it is notable that the choice of the hamster wheel, a ball-looking object, supports the somewhat counter-intuitive behaviour of the wave. It would be more difficult to guide a floating ball on water compared to a surfboard.

The further development of *Hamsterwave* was partially managed under the project management of the QBB (see Section 6.1). However, *Hamsterwave* was considered a counterexample of a successful citizen science game and failed to gather the interest of all the members involved in the QBB project. Although we attempted to find a solution to connect the position of the hamster to the population of the right-most well, we were working with limited resources in terms of manpower, time, and money, which, under the QBB project, were instead focused on *QWiz*, presented in the next section. Consequently, the interaction between the developer and the physicists was not sufficiently catered for, and communication between them was restricted to online messaging and only a couple of face-to-face meetings. It is common for game jam projects to not be further developed after the event, leading to a decline in communication between team members. However, this case serves as an example that even a functioning and attractive game cannot be transformed into a successful citizen science game without the full involvement of a researcher expert in the field.

Drawings, pictures, and versions of the game were used in the communication process, but due to limited budget and time, the game could have benefited from further development in order to have the potential to be a successful citizen science game. Whether *Hamsterwave* could have been transformed and tweaked enough to serve as a crowd-sourcing tool remains unresolved.

## 6.3 QWiz

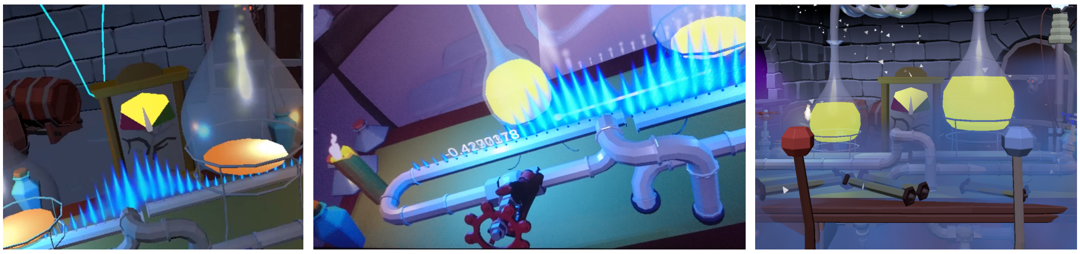
QWiz is a citizen science game developed to investigate the behaviour of a unique liquid controlled by two levers in a magical lab environment. The liquid is contained within a system of two conical flasks linked by an intricate arrangement of glass tubes placed on a laboratory work bench (see Figure 6.8). The game's objective is to transfer the liquid from the left flask to the right flask using the red and blue levers. *QWiz* was developed in Unity and is available on VR, PC, and touchscreen devices. QBB is run on a remote cloud service, which allows for multiple active instances of the simulation and the centralised collection of game play data.


Figure 6.8: A screenshot from the browser version of *QWiz*, a citizen science prototype. In *QWiz*, you use two handles to control the position of the blue flames underneath a intricate structure of glass flasks on a workbench and aim to transfer a liquid from one to another.

The liquid's behaviour in *QWiz* is governed by quantum mechanics principles, simulated by the QBB described in Section 6.1. The two conical flasks represent the leftmost and rightmost potential wells of the QBB, while the connecting tubes represent the middle well (see Figures 6.9 and 6.8). The level of a colour-changing liquid in these flasks is determined by the population number of the wells. Control of the positions of the leftmost and rightmost potential wells is provided to the player through the two available levers, and the relative positions of the leftmost and rightmost wells are visualised by a line of bluish flames underneath the flasks (see Figure 6.8).

Figure 6.9: Three sequential frames from the VR-version of *QWiz*, a citizen science game using the Quantum Black Box (QBB). The screenshots are taken from the presentation video made of the game. The player controls two levers by moving them left and right. This controls the position of blue flames underneath a structure of two flasks and a tubes. The aim is to move the liquid from the left flask to the right one and once achieved, the player is rewarded with a potion bottle (last picture). After receiving three potion bottles, the player receives a point score.

The game has three difficulty levels: easy, medium, and hard. Each level has its own criteria for indicating success to the player and attributing a numerical value to that success. A pointer indicator on the table provides feedback on performance by indicating green when points are accumulated (see Figure 6.10a). The difference in the difficulty levels is governed by individual thresholds for the population of the target potential well on the right. On easier levels, this threshold is reached sooner, therefore accumulating point score and indicating green on the pointer. The rate of score formation remains constant, as it is based on actual elapsed time rather than the time steps defined in the QBB simulation on the server. This ensures that the game provides continuous feedback, even if there is some latency in the network between the QBB simulation and the game.



(a) (b) (c)

Figure 6.10: Snapshots from the game *QWiz*. (a) A point-indicator was set at the centre of the workbench to indicate the direction of point accumulation. (b) A screenshot from the early version of *QWiz*, where valves were used to control the placement of the blue flames. (c) The valves were changed to levers, as they were seemed more intuitive to use.

A numerical score is calculated based on three rounds and is displayed on a leaderboard at the end of the three-round cycle. The higher difficulty levels allow players to achieve the highest scores. This scoring system serves as a motivational tool, encouraging players to attempt more challenging levels that align with the actual scientific objectives of the game. The hardest level offers the closest connection to the actual simulation and allows for a longer simulation time. In this sense, the first two levels can be viewed as a two-step tutorial. The connection the game has to actual research is also presented in the game as a separate functionality with an info board situated next to the workbench in the VR version and behind a menu item on the browser version (see Figure 6.11a).

### 6.3.1 Team

The game was developed through a collaboration between the research group behind QBB and the game development company MiTale over the years 2019 and 2020.


(a)


(b)

Figure 6.11: QWiz is a citizen science game prototype using the Quantum Black Box (QBB) (a) The game has a separate functionality promoting outreach, where the relations of the games to actual physics research are explained (A snapshot from the presentation video of QWiz). (b) A picture taken at the Science is Wonderful exhibition in September 2019, Brussels, Belgium. Marie Curie (actor) playing the VR version of *QWiz*.

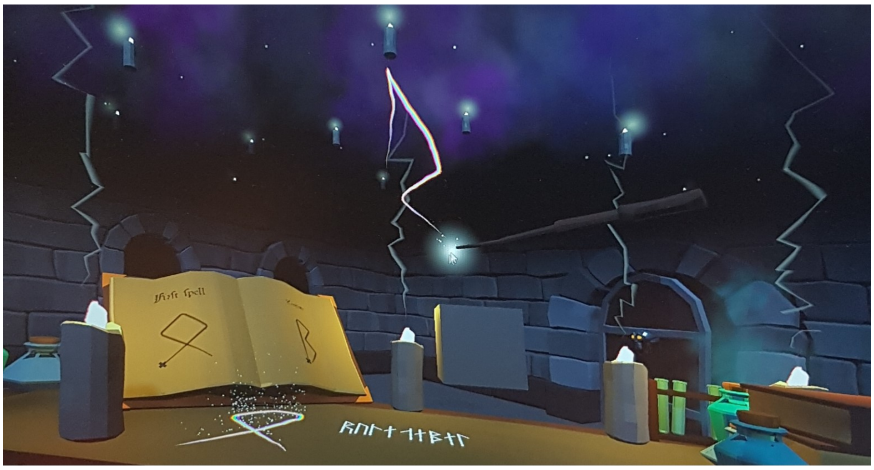
MiTale provided talent and expertise especially in game design, 3D art, Unity, and programming through the active involvement of multiple developers. Natasha Skult, Mikko Lainio, Oskari Tammela, and Joni Salmela were involved from the beginning. The company was responsible for creating the game interface, game mechanics, art, and sounds. Game design was discussed together with the whole team in bi-weekly meetings. In addition, active discussions were ongoing on the messaging platform Slack, both in public channels accessible to all team members and in private messages. An online server running QBB was developed by MiTale and set up in close collaboration. For this project, a total of five quantum physics researchers from the QBB team were actively involved in the design, team meetings, and development process; Matteo Rossi, Nicola Lo Gullo, Boris Sokolov, Walter Talarico, Sabrina Maniscalco and myself. The build of the server and the structure was handled by Joni Salmela, Matteo Rossi, Boris Sokolov and myself.

I had the opportunity to be involved in this project from the initial brainstorming and prototyping stages up until the end of 2020 when the project was handed over from the game development company. I also had the chance to exhibit the game both in Finland and Belgium, seeing it played by hundreds of people of different ages and backgrounds and receiving feedback from these experiences (see Figure 6.11b).

### 6.3.2 The Design Process

The design process behind *QWiz* was initiated with the intent to fulfil a project objective related to the development of the QBB: a fully functioning VR citizen science game. A couple of brainstorming sessions were agreed between MiTale and the QBB team of researchers for creating ideas for such a game. During these first meetings, a couple of different game ideas were inspired by the Finnish game *Snake* and by the Quantum Game Jam 2019 game *QSpell* (see Figure 6.3). *QSpell* is a game for PC, which uses the QBB to create visual feedback based on the movement of a wizard's hands. The hand movements are determined using the keyboard. The use of hand movements of a wizard in *QSpell* motivated the team, as they were seen as something that would translate intuitively to adjusting controls in a VR game. During the first meeting, the team decided to transform both ideas into simple playable concepts that illustrate the functionalities of these games (see Figure 6.12). The team then decided to develop the latter further as a VR game and it was soon named *QWiz*. The team agreed that the game itself would be designed to be intriguing and attractive, but at the same time give informational feedback to the players on whether they are doing well or not. Additionally, the team aimed to develop *QWiz* to handle various optimisation problems, not just the QBB, and for this reason more representative visualisations of the studied problem are not visible in the design of the game. This approach contrasts with games like *Quantum*


(a)



(b)

Figure 6.12: Screenshots from two early playables in the brainstorming phase preceding *QWiz*. (a) A 2D puzzle game, where here the Finnish *Snake*-game was proposed as a base for a citizen science game running the QBB. (b) This VR playable was taking advantage of the free movement of a magical wand for drawing magical shapes corresponding then to parameters entered to the QBB simulation.

*Moves 2* and especially *Foldit*, which prioritise visual representations of the specific mechanics they explore.

Initially, the game was designed around hand movements to draw shapes in VR.

However, as development progressed, this approach was deemed too challenging to relate to the core problem. Consequently, MiTale's designers introduced the concept of a workbench with an intricate system of glass bottles and tubes, two valves and a line of blue flames indicating the positions of the side-most potential wells in the simulation. These valves control the placement of blue flames underneath a system involving two bottles and a complex tube system (see Figure 6.10b). The playable version proved to be difficult to handle as the turning of the valves did not feel like a good enough representation of the moving wells and thus the valves were turned in to levers (see Figure 6.10c). This version was considered to have an intuitive representation of the position of the potential wells and the population numbers of the QBB, but the challenge turned out to be the representation of the dynamics of the system in a way that could be considered intuitive enough to provide feedback. For this, the MiTale team proposed the point indicator and as it was important to the researchers to follow the shape of the original plot in the QBB, it was introduced as an electric arc type effect at the back of the work bench. The visual queues of the blue flames and the electric arc were primarily made for the research team to follow the incorporation of the QBB, but they were design also as visually suitable and supporting visuals for the game experience.

The design of *QWiz* was driven by the aim of creating an engaging and accessible experience, catering to both enthusiasts and those unfamiliar with quantum physics or citizen science. The team wanted to avoid forcing players to download anything, allowing the game to run freely on virtually any device through a browser. This approach was intended to make it easier for players to try the game and reduce device requirements. This led to the development of a cloud-based server for the QBB. The heavier optimisation algorithms were run on remote servers and the game graphics and mechanics were run locally. The team set up a cloud-based virtual machine, allowing multiple users to access a QBB simulation simultaneously.

*QWiz* was incorporated to the online educational platform *QPlayLearn*, after which the active development of the application was sustained. Given the multiple versions of *QWiz* for different devices, updating all versions is time-consuming. For the possible further development, it should be clearly stated that time should also be reserved for complete testing of all these versions, as different deployments may work with varying efficiency and offer different types of user experiences depending on the device used. Emphasis was placed on the WebGL version, as it can reach the largest audience and hence has the most potential as a possible citizen science game. The game is still available in the online learning environment, but upon examination, does not seem to be connected to the QBB server [36].

### 6.3.3 Project Reflections

The development of *QWiz* was an ongoing project for several years, starting through face-to-face meetings and evolving into a remotely working online team collaboration. For the most part, communication within the team was straightforward, and a common language between the two disciplines was found.

To refine *QWiz* as a citizen science game that supports optimal control research in quantum technology, comprehensive testing would be essential. A large assembly of players should be gathered to play *QWiz* for a set period or several rounds per difficulty level. The different levels should also be compared with one another using equal-size test groups to see if there is any indication of a single player gaining better results and whether any of these levels allow the players to reach optimal solutions or solutions close to the known solution. If not, the next actions should be discussed to develop the game in such a direction or question whether it offers an intuitive enough interactive platform and further study which of the visual guides best serve the player. At the stage where the game works as a proof of concept, tests should be issued for a more complex problem instead of the simplification that is run by the QBB. After refining the game through various iterations, the primary aim would be to gather player data and leverage reinforcement learning to enhance the solutions further.

During the annual Quantum Game Jams I have organised, and throughout the extended development of *QWiz*, it became clear that developers and quantum physicists often approach tasks differently. It is evident that neither group can fully grasp the intricacies of the other's profession, emphasising the need for mutual respect in these multidisciplinary projects. On the other hand, I witnessed individuals downplaying their own abilities to follow a discussion or perform a task that was related to the expertise of the other discipline. A more encouraging environment might have proved useful. Unlike a typical Quantum Game Jam quantum game developed over a single weekend, *QWiz* benefited from more dedicated quantum physicists and extended development time. This allowed the team to find a suitable way of communicating that supported both sides.

From *QWiz*'s development, it became clear that crafting a serious game tied to quantum physics research is a complex task and demands significant time and effort. Creating a game that is amusing, entertaining, and captivating is a challenge by itself, let alone having the game then act as a tool for solving a particular mathematical problem. As the participants had already collaborated through the development of the QBB Unity integration (presented in Section 6.1), early in the brainstorming phase the team had found a common language. Still, in the early phases of the collaboration, I noticed multiple gaps in communication between developers and quantum physicists. Some creative ideas were quickly dismissed without thorough exploration, and some suggestions were understood as design decisions. These early challenges related to communication might have been the main reasons why the game does not seem to offer intuitive feedback to the user, though attempts like signalling things set on the table were added at later stages of development. Re-evaluating original design decisions between the early drafts of Figure 6.12 and the drastic changes to the final version of *QWiz* might have been helpful. However, it is essential to remember that we aimed to create a game versatile enough for various optimisation problems. This objective suffered from the lack of other testable optimisation problems and so far it is debatable, whether *QWiz* reached this design goal.

*QWiz* successfully promotes playfulness and curiosity, and encourages players to experiment without fearing mistakes. I believe that the game's inspiring environment, which lacks any technical depictions of the underlying theory or simulation in the main gameplay, significantly influences these aspects. The prototype was also nominated at the Finnish Game Awards 2020 in the serious games category and received great amounts of positive feedback in showcase exhibitions.

## 6.4 Lemminqs Condensate

The *Lemminqs Condensate* is a puzzle game in which the player guides small characters from an entrance hatch to an exit door by controlling the horizontal position of these two doors (see Figure 6.13). Changing the horizontal positions of the doors affect the shape of a wave, on which these characters float. The aim is to maximise the wave on the position of the exit door. The game was developed using Unity and was published through Itch.io as a runnable 'EXE' file download for PC. The game also requires a specific version of Python due to including the QBB simulation.

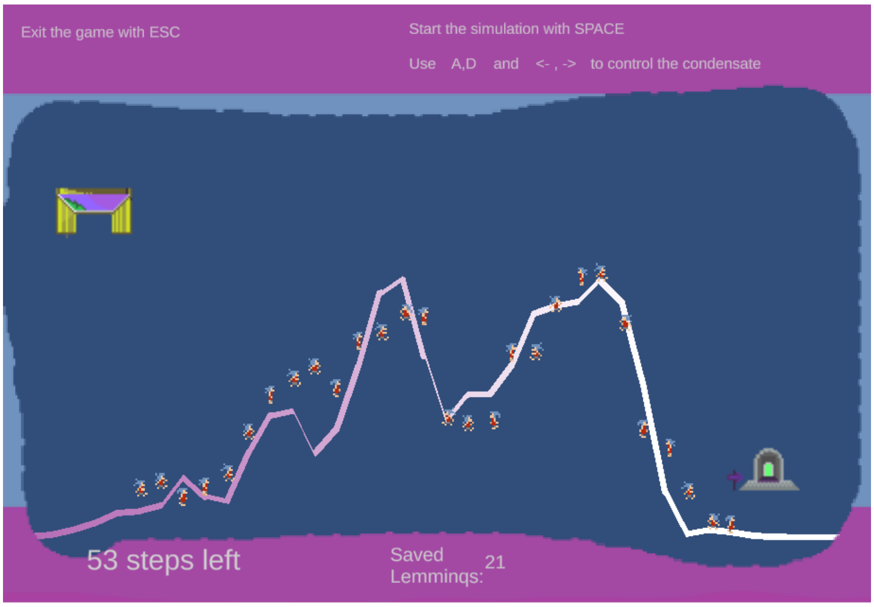



Figure 6.13: The game *Lemminqs Condensate* is a game jam game using the Quantum Black Box (QBB). In the game the aim is to have the lemming type creatures reach the exit door on the right-hand side of the view and this is done by controlling the shape of the wave depicted across the screen by changing the positions of the doors.

*Lemminqs Condensate* was created during a quantum physics-themed game jam organised as a part of the *Games Now!* game design lecture series in 2021. The game was created as a solo project under the time constraints of the event to serve as a citizen science game prototype. *Lemminqs Condensate* runs the QBB simulation, which defines the shape of the wave in the game. The positions of the leftmost and rightmost wells are represented by the two doors.

### 6.4.1 The Design Process

The idea of the game was already developed before the game jam by me, but prior opportunities to bring this idea to life had not presented themselves. I had suggested it at the initial brainstorming related to *QWiz*, but the idea did not gather support. It was later again brought up by another team member, but at that stage a lot of effort had already gone to developing the concept of *QWiz*. Originally the idea was to adapt the probability distribution simulated by the QBB into a wave of multiple *Lemmings*-inspired characters to represent the idea behind Bose-Einstein condensates; under certain conditions multiple separate atoms start to behave intrinsically like a single entity.

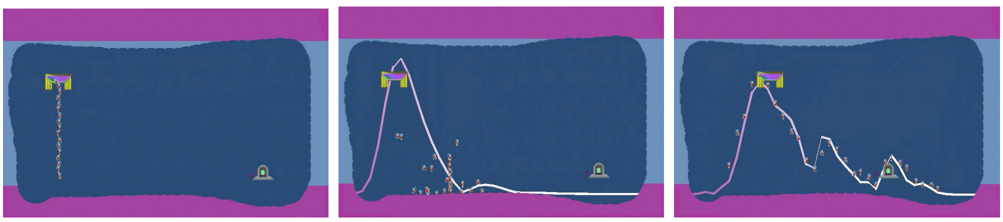


Figure 6.14: Three sequential frames from the *Lemminqs Condensate*, a game using the Quantum Black Box (QBB). As the simulation initialises, the Lemminqs characters are set to stage in a process called "Cooling the Lemminqs down" (first picture). Once the simulation starts, the QBB draws a plot of the probability distribution for the system and the positions of the characters are then tied to this plot (middle picture). The user then uses the keys A,D and arrow-keys Left and Right to control the opening door (hatch) and the exit door respectfully as the characters ride the plot (final picture).

*Lemmings* was a strategy game originally developed by DMA Design and published by *Psygnosis* for the Amiga in 1991. As in the original *Lemmings*, in *Lemminqs Condensate*, the idea is to guide systematically behaving characters to an exit door located in the landscape. In *Lemmings*, the lemming creatures move forward unless they are directed otherwise by the player or encounter an obstacle. In *Lemminqs Condensate* the position of the characters is determined by the probability density plot derived from the QBB. In order to guide the player to try to populate the right potential well for QBB, the exit door is connected to the horizontal position of the right potential well (see Figure 6.15).

*Lemminqs Condensate* draws inspiration also from previous citizen science games related to quantum physics. Specifically, something that has been distinctively prominent in all the versions of *Bring Home Water* and *Quantum Moves 2* as well as in the core of *Quantum Composer*, is that they visualise the probability density describing the system as a liquid. Probability distributions have been used to characterise systems like in these games in the research of quantum systems. Adapting this visual representation for a citizen science game has offered an intuitive way of comprehending the aim of the game [175]. It was therefore a driving design guide for *Lemminqs Condensate* to use the plot simulated by the QBB as a central game element. This decision and a strong interest in incorporating *Lemmings*-type characters into the game were the main design guidelines for the components of the game. The game *Quantum Fruit* presented in Section 6.1 offered another important design guideline for the usage of the QBB in developing *Lemminqs Condensate*: multiple rounds of trials in an iterative manner. This may provide a forgiving environment for trial and error.

The process of developing *Lemminqs Condensate* was spanned over a single weekend at the end of the *Games Now!* game jam week. The goal was to reach a functional representation of the design idea to communicate the basic mechanics behind it. The aesthetics were designed as simple pixel art to respect the original game of *Lemmings* and a decision was made not to incorporate any sound effects of music due to limited time resources. All visuals were created using Microsoft Paint. Most of the time used for the project was spent on incorporating QBB into a Unity project in a way that would connect the positions of the animated characters evenly to the level of the probability distribution. The example game developed to accompany the Unity distribution for QBB provided a starting point for the development. For further developing the game, it might benefit from having considerably more Lemmingqs characters and from an animation where they would shift in (and out) through the exit door as the population of the right-well is rising (lowering).


Figure 6.15: The opening screen of *Lemmingqs Condensate*, a game using the Quantum Black Box (QBB).

### 6.4.2 Project Reflections

At its current stage, *Lemmingqs Condensate* is a prototype game that represents the original idea well. The design restrictions and restricting design guides in the project were time, having only a single member in the team, and the meaningful use of the QBB. The guiding design features for *Lemminqs Condensate* were to incorporate the core characteristics of the lemming characters from the original *Lemmings* and to provide a visually evident representation of the shape of the plot provided by QBB. The strengths of this project lie in the developer's understanding of the main goals of the QBB project, mastery of expertise in the theory of quantum physics, and familiarity with game design and game development on Unity. At the time of creating *Lemminqs Condensate*, I had finished university-level courses on interaction design, game design, and game development, and had been part of several other game development projects, but I was still far from being a highly experienced game developer, let alone a professional. I feel this shows in the game.

It is particularly interesting to compare this outcome to the previously presented games where communication between the different representatives of expertise was considered a hindrance. By looking at the game, we may conclude that the aesthetics of the game do not compare to the previous ones, but it has been a design decision to compromise aesthetics over functionality within the limited time presented for the development process. The game design in *Lemminqs Condensate* was a process that did not meet my full vision, but the game does present the intended mechanics. The development process was fairly straightforward as the concept idea behind the game had been formed in advance. The main value of the *Lemminqs Condensate* is that it is a working prototype for communicating not only an idea of a citizen science game but also the mechanics and functionalities of it.

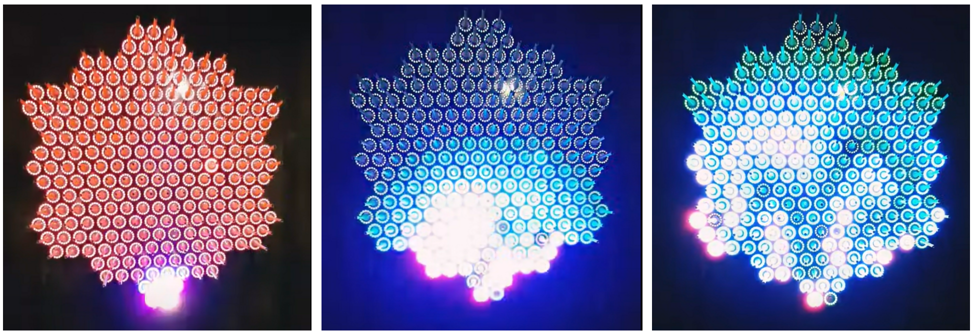
## 6.5 Quantum Garden

*Quantum Garden* is a playful, interactive light art installation consisting of a board of LED lights connected to over 100 springs (see Figure 6.16). The touch of the springs transmits a signal for the computer to process and determine a response as a visual simulation of the LED lights. As the player touches one of the springs a second time, another visual simulation indicates an outcome dependent on the chosen values. *Quantum Garden* demonstrates key concepts of quantum physics, such as quantum superposition, interference, and the Schrödinger equation through its visual light effects. The LED lights of the art installation are connected to a computer


Figure 6.16: *Quantum Garden* is an interactive art installation based on the concept of *Wobble Garden* by the artist *Robin Baumgarten*. The art installation sits on a plywood stand and consists of a board of door stoppers connected to a string of led-lights.

hidden from the player, which runs a Python-based simulation using PyGame modules in its implementation. The first version of *Quantum Garden* started as a citizen science project that aimed to provide the means for anyone to contribute to the research of quantum physics, specifically to problems that play crucial importance in the outbreak of quantum technologies. For this purpose, the art installation was connected to a numerical simulation of the three-well potential optimisation problem QBB (explained in Section 6.1). The player was guided with the words of "Touch the springs to create a quantum simulation. Find the most vivid combination!". Each of the springs were mapped to represent pre-set initial values, which would then indicate the success of that specific choice of attributes determined by the QBB. This was visualising as a sphere of colours, the ratio of which was proportional to the success. The first version of *Quantum Garden* was exhibited at various locations and was also presented to university and school students incorporated in outreach activities.

The first iteration of *Quantum Garden* with the QBB simulation proved indication that it could serve as a visualisation tool for the wave-like phenomena in quantum systems. This inspired towards the idea of updating QBB to another simulation that would better serve as a visualisation tool in outreach events. A second version of *Quantum Garden* was adjusted to suit a numerical simulation of a *quantum random walker* in a lattice, a model used as an approach to quantum algorithm development and in modelling condensed matter structures [168]. The player was guided to "Touch the springs to unleash the quantum particle!" for the new version. This actions sets a simulation that spreads over the art installation as indicated in Figure 6.17. After this the user makes a guess regarding the position of the walker by touching one of the springs. The placement calculated (randomised) by the simulation is indicated to the user with another light animation. This interactive art piece acted also as the inspirational starting point of *Quantum Playground*, which extends this concept to a VR setting. *Quantum Playground* is presented in the following section.



(a) (b) (c)

Figure 6.17: Three sequential pictures taken from the colourful simulation of *Quantum Garden*'s second iteration, that was using the quantum walker simulation. (a) One spring has been selected from the bottom side of the panel and starts to spread across the network. (b) The quantum walker simulation starts spreading towards the other springs with a colourful wave, where the colour is determined through a probability distribution adjusted to fit a colour spectrum spanning from red to green to blue. (c) As the colourful wave reflects from the sides, we will see interference patterns as the amplitudes of the waves accumulate either by enhancing each other or cancelling each other.

A quantum walker is the quantum analogue of a classical random walker [168]–[170]. A random walker may be thought of as a walker that picks its walking direction at random at each step. A quantum walker then again, instead of being restricted to a single of several provided directions, can propagate through all possible paths in a superposition. Quantum networks are networks facilitating transmission of information between quantum mechanical objects. Quantum networks and quantum random walkers provide a way for displaying certain features of the quantum world and, in addition, are an active field of study within quantum computing, quantum communication, and quantum biology.

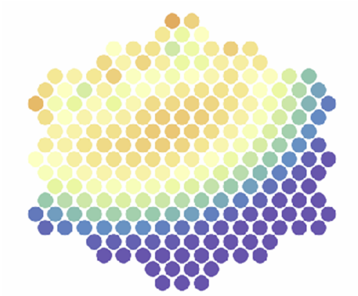
### 6.5.1 Team

*Quantum Garden* was realised by the game artist Robin Baumgarten in collaboration with a team of seven quantum physicists from the research team TQT, and curated by Dr. Annakaisa Kultima of the Media Department (Aalto University). The board of LED lights itself sits on a stand specifically designed for the art installation by Dr. Annakaisa Kultima (see Figure 6.16). The art installation was intended to be a game-like, interactive art piece similar to the previous works of the artist.

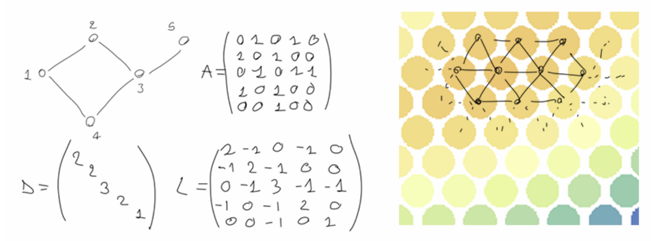
I joined the development of *Quantum Garden* in late 2018, when the original version, running the QBB (see Section 6.1), was planned to be replaced with a version that simulates a continuous-time quantum walk on a quantum network. As I joined the development of *Quantum Garden* around this time, the views presented here are mainly reflecting those of the later version of *Quantum Garden*. The physicists involved in the project during my involvement were Sabrina Maniscalco, Matteo Rossi, Guillermo Garcia Pérez and Walter Talarico. Nicola Lo Gullo and Francesco Cosco were able to help me introduce myself to the QBB connected to the first iteration of *Quantum Garden*, but were no longer actively involved in the development of the second iteration. My role was mainly related to project management and responsible for practicalities related to the art installation, like storing, transporting and dedicating resources. My responsibility was also to contact and then onboard exhibition teams for showcasing the art installation at various locations. I was responsible for communicating the objectives when introducing the piece to a person responsible of presenting and upkeeping the art installation in Brazil.

### 6.5.2 The Design Process

As the researchers behind the QBB project involved with the development of *Quantum Garden* shifted their main research goals from the study of Bose-Einstein condensates to the study of quantum networks and their applications, the simulation behind *Quantum Garden* was also decided to be changed. The team wished to find a simulation that would better serve to visualise phenomena specific for quantum physical systems. For this, the topic of quantum walkers was supposed, as it was also supported by the research topics studied by the group. Guillermo García-Pérez designed a visual simulation for PC using the Python library PyGame, which represented the structure of *Quantum Garden* (see Figure 6.18a). A couple of face-to-face meetings were organised to again bring together the team and the original artist in September 2019. The physicists presented the new idea for the simulation to the artist and the artist presented suggestions for implementation and a walk-through of the electronics developed for the art installation.



(a)



(b)

Figure 6.18: For introducing the new simulation of *Quantum Garden*, an interactive PyGame simulation was developed by Guillermo García-Pérez. This simulation was used in the communication of the projects *Quantum Garden* and also later with *Quantum Playground*. (a) A snapshot of the PyGame simulation of the second iteration of *Quantum Garden*. (b) An illustration used in the communication between team members in the projects using the Quantum Walker simulation (Matteo Rossi).

The structure of *Quantum Garden* with its interconnected strings supported the idea behind the simulation of quantum networks and the members of TQT studying these systems soon coded a PyGame representation of the *Quantum Garden* structure that simulated an excitation in a two-dimensional network as a colourful heat map of the related probability distribution. It incorporated the interactive elements of selecting the initial position or superposition of the excitation in the network and the final selection of a string, which collapses the superposition evolved under the simulation.

*Quantum Garden* had several physical versions that were exhibited around the world and pictures of it are still being used in Aalto University communication [149]. One version of *Quantum Garden* was presented at the Quantum Game Jam 2019, *Quantum Wheel*, and after that at the science park Heureka, where it had possibly its roughest use as over 3,000 visitors explored the park daily. This caused a lot of mechanical wear on the art installation and demonstrated the limits of showcasing *Quantum Garden*. Not having a maintainer present to fix possible physical damages or anything related to running the code was seen as a limitation. As the piece travelled around the world in multiple exhibitions and had several versions of it built, the resources of the team were not enough to accompany all the versions.

### 6.5.3 Project Reflections

As I joined the team in the middle of an already established collaboration, it was rather difficult to get into the team mechanics. The technical details of the first version of the art installation were not well documented and acquiring the documentation also required a lot of effort as everyone I approached always referred me to ask someone else. At the end, no one seemed to be certain on what was actually happening in the art installation and were offering disclaimers like "It *should* do the following". After moving towards the second version of the art installation, I was able to be more involved in the projects and better understand the mechanics behind it and therefore provide updated documentation for the piece. For conveying the idea behind the new simulation, the PyGame simulation provided a valuable tool that communicated the design goals, functionalities and interactive elements well to the original artist, who incorporated the simulation to the art installation (see Figure 6.18). It also worked as an important communication tool in the project

*Quantum Playground* presented in the following section.

Being responsible for the practicalities related to the art installation, like storing, transporting and dedicating resources for these took away some of my resources related to being involved in briefings, such as the introduction of the electronics behind the art installation. It was also unclear at parts, who was actually responsible for what, which led to difficulties in the communication between the team members. It required extra effort to settle such challenges. There was also a considerable lack of resources related to the upkeep of the art installations that were travelling around the world. As some of the exhibitions the art installation was presented at had thousands of visitors daily, the art installation experienced considerable mechanical wear, which led to some parts breaking. We received no reports on the success or challenges of these travelling versions.

Sadly, due to other projects shared by the team, some challenges with communication drifted the team apart and further hampered the logistics of *Quantum Garden*. Important knowledge and connections were carried by a team member who transferred to other projects. Yet, *Quantum Garden* proved to be an attractive, and engaging art installation that provided valuable in outreach events and for educational content explaining some principal concepts of quantum physics. The different versions of the art installation travelled around the world in exhibitions and was included as an inspiring inclusion to introductory quantum physics lectures at the university and high school level.

## 6.6 Quantum Playground

*Quantum Playground* is a VR environment with enchanting colourful simulations and a narrative-driven intro. The player starts with a view of multiple little spheres aligned around them as a spherical surface (see Figure 6.19). From these spheres, the player is guided to choose one or many using hand-guided gestures. After this, the player may start a simulation, which is visualised as a wave-like effect running through the spheres. In this effect, each sphere changes its colour and size. In the last step, the user may again choose one of the spheres and this action then indicates a visual designation on one of the spheres. The aim is to have guessed this sphere right.

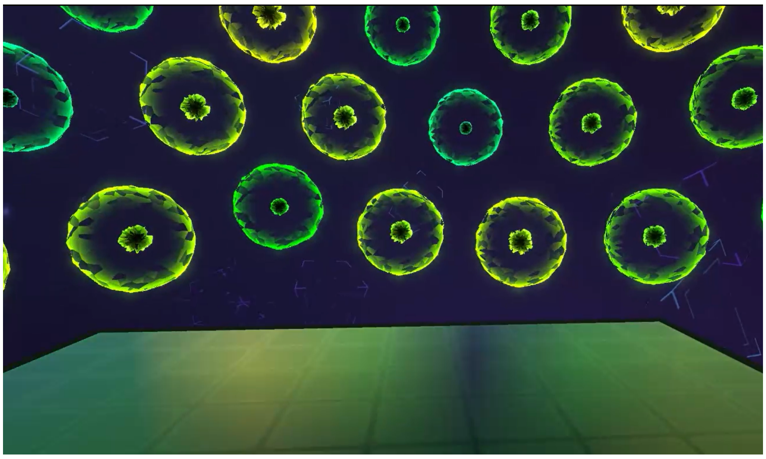
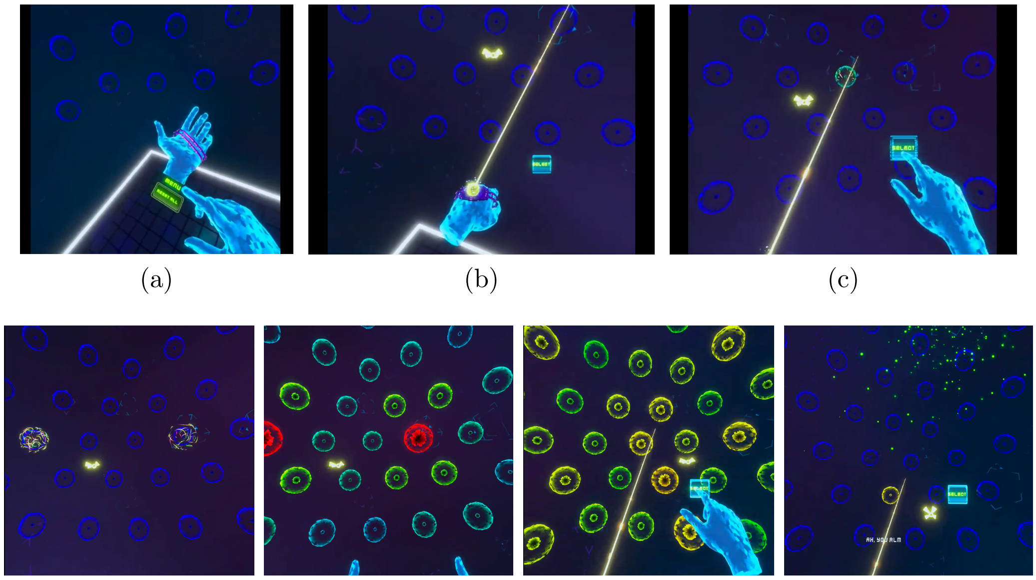


Figure 6.19: A snapshot inside the virtual reality experience *Quantum Playground*. The application runs a numerical simulation of a quantum walker in a network, where the network is presented as colourful spheres that change shape and colour depending on the probability distribution calculated by the simulation.

*Quantum Playground* was developed on Unity and includes a C# adaptation of the quantum walker simulation incorporated in *Quantum Garden*. *Quantum Playground* was developed to serve as a VR installation, a touchscreen and a browser version. During Spring 2020 MiTale and the QBB got together to brainstorm on ways to create a virtual reality version of *Quantum Garden*. The aim was to create a tool, a simulation environment, with which anyone could explore the phenomena of quantum physics through the example of a quantum random walker. The team wanted to face the challenges of visualising the quantum effects without compromising on the connections to the underlying mathematics of the theory, and creating a captivating concept that the end user could enjoy, regardless of their (initial) interest in quantum physics.

The visual effects in *Quantum Playground* are determined by a numerical simulation of a quantum walker presented in section 6.5. Each sphere represents a node in a network. The user can select a node for a quantum walker to start from on this network of nodes, turn on the simulation, and watch the probability density distribution evolve around them. The nodes of the network are presented as spherical 3D objects, whose size and colour are defined by the probability density of the quantum walker's wave function, illustrated in Figure 6.20.



(a) (b) (c)

(d)

Figure 6.20: Snapshots from the VR version of *Quantum Playground* showcasing the interface. (a) Access to the menu and a functionality to resetting the simulations were found from the left wrist. (b) For pointing at the spheres, a beam (in yellow) would be launched from the back of the left hand with a punching gesture. (c) For selecting a specific sphere, the user could click on a separate button with their right hand. (d) From the selected spheres, the simulation of the probability distribution of the quantum walker evolves around the network until the user selects one of the spheres to collapse the spread of the wave function.

### 6.6.1 Team

*Quantum Playground* was developed as a collaboration between the researchers behind the QBB development and the game development company *MiTale* between April 2020 and November 2021. The idea of a VR environment, where the numerical simulation of a quantum walker, familiar from *Quantum Garden*'s second version, would be spread as sphere-like surface surrounding the user came from the researchers.

The development of *Quantum Playground* was subcontracted to MiTale and the collaboration included several on-site and online meetings. The overall development of the application and the numerical simulation tool quantum walkers was a joint effort between the game developers and quantum physicists. Both teams are professionals in their particular fields with years of game development and quantum physics research experience, respectively. Responsibilities regarding the coding of the numerical simulation and Unity development were split between the teams according to their expertise. The physics script numerically simulating the quantum walker (based on a C# script making use of the Math.NET libraries) was designed and written by me and Matteo Rossi. Guillermo García-Pérez had designed the original numerical simulation that was originally written for *Quantum Garden* in `Python` using the PyGame modules (see Figure 6.18a). Sabrina Maniscalco, Boris Sokolov and us aforementioned physicists were all involved in discussing and evolving the design of the application.

The game development team from *MiTale* was responsible for exhibiting their excellence in game and narrative design, developing the UI/UX, and implementing all the components into a coherent, compelling experience and involved Natasha Skult, Aapo Peltola, Joni Salmela and for the art Mikael Perilä. They also had main control over the way of handling the requests to and from the physics scripts and making the final touches on the storyline of the tutorial to make it intriguing and intuitive. Playable versions and videos of the different development phases of the Unity project were shared with the whole team during bi-weekly meetings.

I was deeply involved in the whole development process from the first meeting with Mitale to the hand-over of the application to the researchers. I was responsible for creating the C# script for the Unity project, so that it numerically simulates the quantum walker. For this I created a separate test environment project on Unity, handlers, the call structure and the C# script making use of the Math.NET libraries. The logic and the script for the simulation were then handled together with the main developer of MiTale, Aapo Peltola and another physicist, Matteo Rossi, so that the overall call structure would be more efficient and suit the Quantum Playground structure. I also played the role of a voice actor for the tutorial of the application.

### 6.6.2 The Design Process

*Quantum Playground* started on the base of an already working collaboration of the team behind *QWiz* and an existing interactive art piece *Quantum Garden* presented in Section 6.5. Translating the experience of playing with *Quantum Garden* to a VR environment offered its challenges, but also promised a more indulging experience and opportunities for communicating the idea behind the simulation. In addition, by providing a virtual environment for the simulation the mechanical distress that affected the durability of *Quantum Garden* was addressed.

To introduce the simulation of the application with its functionalities, a tutorial was designed to make the connection to quantum physics and to introduce the UI. The interface of the virtual reality version is introduced in Figures 6.20 and 6.21. As the aim was not to make a stand-alone educational game or to teach quantum physics *per se*, a middle ground between writing an interesting storyline and describing the connection of the simulation to quantum physics was found. In quantum physics,

Figure 6.21: Snapshots from the VR version of *Quantum Playground* showcasing the hand gestures of the interface. The simulation environment was initialised by pulling a spherical object from the back of the left hand. This would then launch the network of of spheres around the user.

measurements are of particular interest, as any observation of a quantum mechanical object impacts the system. So when measuring a property of a quantum mechanical object, like as an example, its position, the wave-like propagation of it collapses to a single position. This was set at the centre of the narrative of the tutorial. Visualising quantum physical phenomena was one of the main deliverables of *Quantum Playground*. The team members maintained close contact during the development process and regular hybrid meetings and an online messaging platform were set to keep the communication between game developers and physicists as clear as possible.

The design of the virtual environment and its functionalities began based on a common understanding of the design idea, but separately from the development of the physics script. As the two were to be combined, the calling structure between the script and the prefabs was discussed throughout. The discussion revealed some need for scaling certain numerics to better represent and communicate the simulation. Together with me and one of the MiTale developers, Aapo Peltola, the rate of simulation defining the size and colour of the nodes was adjusted by setting suitable time steps so that the phenomena to be presented were both visually clear and faithful to the physical system being simulated.

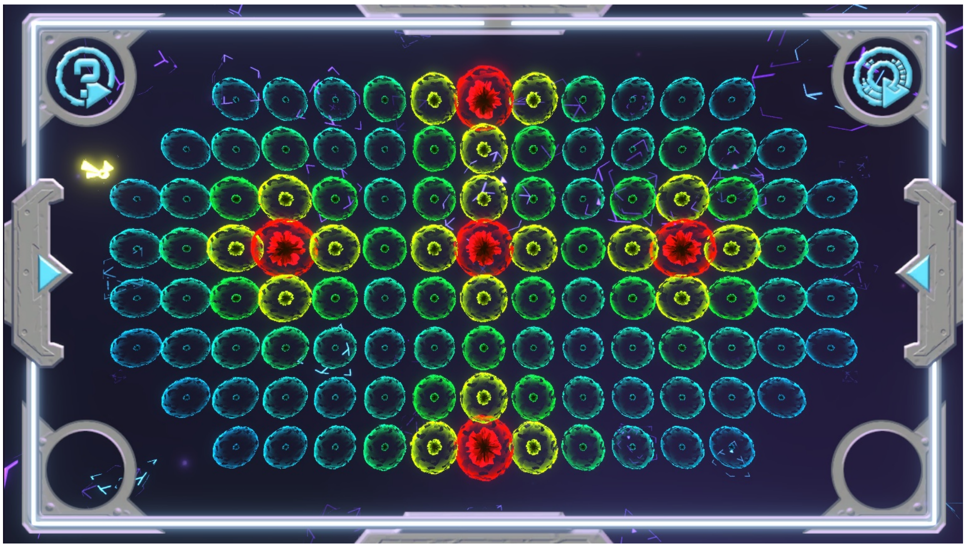


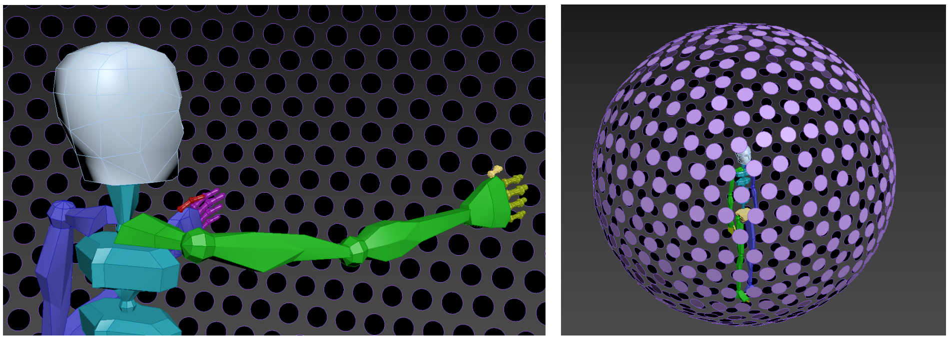
Figure 6.22: A screenshot of the WebGL version of *Quantum Playground*.

As the main functionalities were set, the efficiency of the simulation was addressed. Modifications were made, for example, by separating a part from the physics script to a separate thread by the main game developer, as it seemed to slow the initialising process of the simulation altogether: The script contained a separate procedure for calculating the exponential of a matrix, and it turned out to be the main source of slowdown in the simulation. A physicist was able to optimise that part of the code, resulting in a 40x reduction in calculation time from 1.6s to 40ms. As this was still considered to be too slow to be run in one frame, the threading was kept alongside this change.

After verifying that the script was producing the wanted simulations at a rate notable to the observer and that the colour spectrum appropriately displayed differences between different spheres, the final touches were made by the game developers to produce an appealing gamified experience by polishing the interactive storytelling elements.

A WebGL version of *Quantum Playground* was developed based on the VR version to reach more users. This was of particular importance especially during the time of the COVID-19 restrictions which coincided with the release of *Quantum Playground* [150]. It was deemed too complex to represent a 1-to-1 resemblance of the original network arrangement for a 2D view to suit a multitude of different shape screens. Scrolling the view frame through the network was suggested to be used for navigating, but that could have limited the ability of the user to perceive the wanted effects of the visualisation and was therefore discarded. The network of nodes was decided to be decreased to a number of 108 nodes that fit the view frame with the original spherical objects representing the nodes. The VR developers from MiTale designed an interface to suit the storyline of the application as well as additional buttons for the functionalities of starting the simulation and for getting guidance. On the main screen, the user is able to choose between going through a guided tutorial or starting to play with the simulation without one. A screenshot of the interface of the WebGL version is shown in Figure 6.22.

All of the people – both game developers and physicists – involved in the project had some background in developing games related to quantum physics, but neither group could have been regarded as professionals in both fields. For the physicists, it came down to being able to single out what were the most important aspects to translate into the game from the simulation so that it would benefit as a visual aid to exploring quantum physical phenomena. Physicists also needed to familiarise themselves with Unity, a platform quite rarely used in the field of quantum research, in addition to studying the libraries within C# (the scripting language used by Unity) that could offer the appropriate maths functionalities.



(a) (b)

Figure 6.23: Illustrations of the user inside the *Quantum Playground* VR environment. Illustrations are provided by Boris Sokolov originally for communication within the project. (a) The view inside the network of spheres. (b) The view from the outside of the network of spheres (spheres presented here as round disks).

### 6.6.3 Project Reflections

In the beginning of the project, the team was able to meet in person but were soon restricted to communicating through a common Slack workspace and video calls due to COVID-19 restrictions. This made it somewhat simpler for one-to-one communication between the main developers and physicists-developers regarding specific changes to code, the call structure in the Unity project, and related practicalities. As a rule, not all physicists nor game developers have an extensive background in coding. However, in this development group both teams had experienced coders in them, and this probably aided them to quickly find a common language. Communicating through text made problem-solving efficient and accurate as specific wordings and pieces of code were less prone to being misheard. Vital for the progress was also that the developers had VR equipment available for loan to their home offices during the lock down. Keeping contact through a common Slack relaxed the usual time constraints related to organising a face-to-face meeting and eventually lowered the threshold for starting a conversation. In a way, the other team members working at different locations were closer.

The early in-person meetings served an important purpose, as a lot of non-verbal communication, bonding laughter, and crazy ideas might have been lost if the creative phase had been restricted to being online. For describing the initial idea the 3D model in Figure 6.23 was crafted and ideas on adding the visual elements on top of this model were presented in a VR prototype to the team of physicists to comment and admire. These visual ways of communicating were crucial to the communication.

In Figure 6.24 we have a screenshot of a video from the Unity scene that was used to communicate the state of the project between a developer and a physicist through Slack. In addition to the sphere of nodes, the environment had additional dynamic, purely visual effects, like the blue ray visible in the picture. Videos and screenshots with added annotations helped to adjust, for example, the appropriate scaling of the chosen colour spectrum to make differences in the probability distribution more visible to the user, as well as to respect the numerical quantum simulation. Particularly, when adjusting the rate of the simulation, videos were of high importance; quantum mechanical effects are fast and delicate, so it is important to adjust the rate of the simulation appropriately to make the phenomena visible to the user.

## 6.7 Concluding Reflections

The five quantum game and quantum physics-related interactive art pieces presented in Chapter 6 represent a variety of different types of design journeys. In this section, general conclusions on the lessons are presented and any project-specific lessons are separately provided to support covering the diversity of these processes.

For the meetings between the physicists and game developers, there were often as many as ten people present. As everyone participating was also enthusiastic to

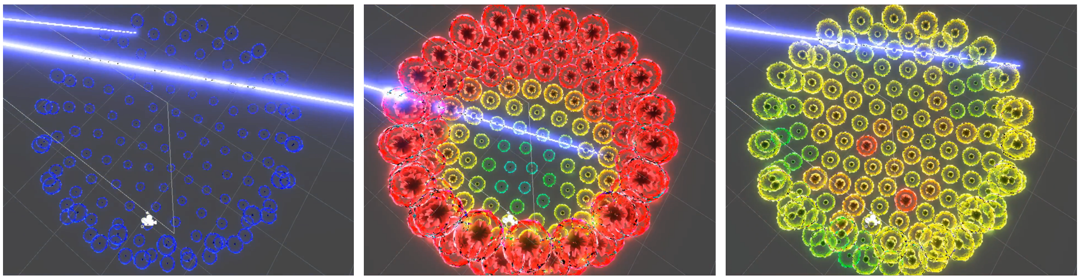


Figure 6.24: Screenshots from a screen recording that was done from the Unity project of the virtual reality version of *Quantum Playground* used in communication during the project. In the development of *Quantum Playground*, screenshots and videos from the Unity project were used in the remote communication between team members. In this version the colour scale was opposite to the one in the final version.

present their ideas and views, it was difficult for some members to keep track of what was happening at times or to raise their voices. To address such situations, it became crucial that there was a designated person collecting meeting notes and keeping track of the general design process as well as the design decisions picked up from brainstorming sessions for example. This enabled the team members to recap the process and ensure that the team was in line with these decisions and that possible misunderstandings were promptly addressed. I noticed many times that the more reserved team members might have stayed quiet during these meetings, but would present valuable and innovative solutions to presented dilemmas later on. A meeting culture, that would share the floor more evenly might support better the sharing of ideas, but leaving room for later additions to design decisions might prove more approachable to certain types of people.

To me, it appeared that it was much easier for the game developers to keep on track with the brainstorming and design process altogether. This is mostly due to the fact that in most of the presented projects the developers were highly experienced of such experiences. Especially in projects *QWiz* and *Quantum Playground*, the members already had a background in designing serious games. This experience provided them with means to track the deliverables and possibly also to read the client's needs.

Although no structured testing was organised, most of the projects were presented to the public and were played by hundreds. *Hamsterwave* and *Quantum Garden* were exhibited at Oodi Library, Helsinki at an exhibition organised between the 21st and 29th of September 2019. Both of these pieces attracted a lot of interest. *Hamsterwave*, *Quantum Garden* and *QWiz* were also exhibited at the *Quantum Explorations* exhibition organised in Espoo, Finland, alongside the European Union's annual Quantum Flagship meeting, *the Exploring and Making Quantum Technology* conference in October 2019. The opening exhibition was visited by technology researchers and experts, but was then opened to the general public for some months. The exhibition also travelled to Western Finland in a smaller scale and on both occations guided tours were organised for school groups..

Projects *Quantum Garden* and *Hamsterwave*, in particular, were very successful in creating interest and seemed to lower the threshold to try, play and get to know the artefacts. Exhibition visitors gave positive feedback on *Hamsterwaves*'s visuals, the cute hamster attracted many, and the aim of the game was straightforward to understand. *Quantum Garden* was admired as attractive, stimulating and highly distinctive in comparison to other exhibition pieces. Especially younger audiences were intrigued to touch and play with it and the simulations were admired, but it was commented to be harder to understand the aim of this playful creation. It could have benefited from visual cues explaining its aim and inner workings, but still served as a piece for starting a discussion with physics experts presenting it. *Quantum Garden* and *Hamsterwave* work as proofs of concepts in showing the importance of an attractive, visually appealing and working user interface in the development of games and art for outreach and education. Sometimes an attractive artefact was enough to start a conversation, which could present an opportunity to teach about the physics involved and would encourage testing the other artefacts and games. This observations underlines the importance of designing the overall visual appearance as well as the important role of game design in the development of quantum games.

In the beginning of exhibiting, *QWiz* was mainly showcased as the VR version, which seemed to limit the interest of certain groups of people, but also attract other types. Dressing on the heavy goggles and having them touch your face is found awkward by some, in particular when served with the idea that you would have to share the equipment with hundreds of other visitors. For some the novelty of VR was found alluring. In the *Science is Fun* exhibition in 2020, *QWiz* was played by hundreds of school children both as a VR game as well as a mobile, touchscreen version, and as a PC version, but required some motivating and inviting of users. A large screen showcasing the actions of the person using the VR was found very entertaining and worked as an invite to try the game out. Still, oftentimes the player would instead start to explore and admire the VR environment or even open up another application in the equipment, so extra attention and supervision had to be provided with the showcasing. To me, it seemed that the choice of the VR equipment was limiting the accessibility and general use of the game, but on the other hand it was often the very thing that made people come and start a conversation. The touchscreen and the webGL version on PC were at times able to lower the threshold to "come and poke" and was therefore able to lure people closer and spend time playing the game. It is therefore important to evaluate the platform and audience to be suitable for the purposes of the game.

Although some projects presented in this thesis have sprung from an initial interest towards quantum games and have had strong intrinsic motivators, some of them were not finished. Obviously, any large-scale project requires manpower, money, and time to be a realistic one. If any of these elements lack substance, the project is in danger of being terminated before meeting design objectives. For *Hamsterwave*, resources to further develop the game jam version of the game were limited. For *Lemmings Condensate* there were no resources or motivation for further development within the QBB team. This may also be due to the general project behind QBB coming close to an end.

CHAPTER 7:

# Discussion

We have explored five distinct project types alongside the development of a simulation tool designed for citizen science game development. In these endeavours, my involvement has ranged from serving as a consulting expert to being deeply immersed in the development process, and at times, functioning as a solo developer. My expertise stems from a background in theoretical physics and the study of quantum foundations and phenomena. With the exception of projects undertaken during graduate-level game design courses, these ventures mark my initial involvement in game development. For quantum game developers in general, such a background is not rare. Quantum game development is not a field with a long history, and the lack of extensive experience in game design and game development characterises many of the creators of quantum games [10], [12], [13]. The project descriptions presented in this thesis are invaluable for comprehending the current landscape of quantum game development and facilitating the dissemination of knowledge within the field. Moreover, sharing insights, even those that may seem simplistic or evident in hindsight, fosters opportunities for reflection. Each project outlined in this thesis possesses unique attributes, both in terms of their outcomes and the developmental processes underpinning them, thereby furnishing a valuable cross-section of quantum games and playful quantum physics-related artefacts.

The role of visual communication in quantum game development has been deemed of great importance and was proven central also in the presented projects of this thesis. From the perspective of a visual designer, building upon previous work and existing fantasy has been proposed as ways to tackle the challenges of producing quantum game design ideas [117]. Although this approach may be beneficial particularly in the communication between disciplines during the development process, it may hinder the formation of new types of quantum games. Additionally, one should be clear about the differences between the classical and the quantum analogues whenever relying on the usage of classical analogues as examples to avoid creating misconceptions, which might further translate to the interface of the game. This becomes of particular importance, when designing educational quantum games, as the design of the interface of a visualisation tool and the interaction with it affect greatly how students are able to learn quantum physics [11], [176], [177]. As an example, in [176] the observations made of students using a simulation tool and student interviews revealed that using colours to represent the phase of a function was not seen as useful as separately representing the real and imaginary part of the function. The "phase colour" representation and was even causing significant problems upon interpretation.

The approach of building upon existing fantasy may prove useful particularly in game jam events, from which the cited work gathers most of its insight, but may, in general, lead to a definite and deprived pool of games. The potential as well as the challenge of quantum game development is that of the theory of quantum physics has been to the study of physics; how may these marvellous phenomena and properties of nature benefit and challenge our perception of what we know? Without facing the unknown, challenging the known, and trying out new things despite the fear, we will never gain anything new and conceptually wonderful.

The visual representation of quantum physical phenomena familiar to scientists may prove useful in designing the visuals of a serious quantum game. Shaeema Zaman Ahmed presents her studies and involvement in quantum games in her thesis *Quantum Games and Simulations* [11]. She does not provide extensive descriptions of those processes. The thesis primarily focuses on describing the artefacts, but includes descriptions of the author's responsibilities and involvement in the development processes. The investigation into the citizen science game *Quantum Moves 2* revealed that players developed intuition about the game, likely due to its straightforward visual representation of the probability distribution. This is in contrast to *QWiz*, where the central process is not visually emphasised for the player. In *QWiz*, the strange, intuition-defying nature is not centrally visible, but instead, certain measures of success (population of the rightmost well and the fidelity) are visualised through the levels of the liquid and a separate scoring system behind the point score indicator on the workbench. Further study could provide insight into the importance of selecting appropriate and specific visual representations. However, the decision not to limit the game interface to simulation-specific visual representations in *QWiz* was a deliberate design decision in creating a versatile game applicable to various optimisation problems. This challenged the team to find ways to visualise the dynamics of the studied problem from other perspectives. Still, a similar type of visual representation to the one present in *Quantum Moves 2* was used to aid communication within the team along with analogies to classical models of liquid. We see how these analogies and visual language translated to the end product, the game artefact of *QWiz*, in which the focus is in the behaviour of liquids.

Further exploration of the limitations of visual representations for complex problems in interactive systems would have been particularly intriguing. This poses the challenge of finding the appropriate balance between visually representing specific aspects of simulated problems and ensuring the game's generality to address various optimisation challenges, thereby fostering player intuition of underlying mechanics. Examining player tactics and identifying factors that contribute to player intuition of underlying problems will offer valuable insights for the development of citizen science games in quantum physical sciences. Assuming prior knowledge of what best serves player motivations without studying previous projects can be a critical pitfall. In particular, it is not beneficial to the development of these games if the projects are pursued without also understanding of what motivates players towards citizen science. Ultimately, citizen science games aim to uncover insights into research problems beyond the capabilities of computer-aided algorithms alone. Therefore, fostering motivation for participation is of great importance here.

The previous works investigating the design process of games and art related to quantum physics have mainly focused on differences and miscommunications between the physicists and other team members [12], [117]. It is important to note that miscommunication can also happen among people with similar backgrounds, but especially in situations where discussions about the project's connection to quantum physics involve members without prior backgrounds in quantum physics or quantum games. Design decisions based on information from such discussions may have significant consequences in the project cycle and be more challenging to rectify. This could have been the case with *Hamsterwave*, where expert involvement in the project was lacking after the initial brainstorming. Attempts were made at the end of the development process to better align the mechanics with the citizen science objectives, but this goal proved too challenging given the available resources. Despite being created within a single weekend under the challenging theme of quantum physical phenomena, *Hamsterwave* excelled as an attractive, well-balanced game with an intuitive goal and a pleasant gameplay experience, as observed in multiple events. This can be seen as an indication of the importance of game design talent and expertise from the early stages, emphasising the need for involvement of game design expertise.

In addition to understanding the importance of developing an attractive, easily approachable interface, it had become clear that for applications intended for educational purposes, an expert in the field and a professional for designing possible numerical simulations are needed. But having a visually accurate interface is not enough. Particularly in today's digital age, where attention is divided among various social media platforms and games, the attractiveness of the application plays a big importance. Attractiveness and intriguing game experience play a central role in motivating outreach projects in quantum physics, as we cannot just rely on the initial interest of the public in joining a research endeavour. A talented game designer and talented visual designer are able to tackle such challenges and through inclusive collaboration with the field expert, the interface can be both attractive and respectful for scientific principles.

In the projects *QWiz*, *Lemmings condensate*, and *Quantum Playground* the team members had previous experience in developing playful creations related to numerical simulations of quantum physical phenomena, particularly in using the Quantum Black Box (QBB, introduced in Chapter 6). Compared to the project *Hamsterwave*, which relied on a presentation of the tool at the event just shortly before brainstorming, many members of the other presented projects were already familiar with the simulation tool. The earlier possibility for play and experimentation with these simulation tools may have helped with exploring the possibilities for their usage, but particularly helped the communication, idea building, and setting technicalities within the team.

Particularly when restricted by the short time interval of game jams, for designing a citizen science game prototype, it became clear that teams needed a committed, actively available physicist with an understanding of the underlying problem related to the QBB, as well as the deliverables of the end product, to design a viable citizen science game prototype. Also, this person would have to be able to commit to the project from start to finish. The teams that had a dedicated quantum physicist who was already familiar with the problem behind QBB were also the teams that were able to produce citizen science game prototypes that allowed the player to reach for the known solutions. On the contrary, the teams that had no physicists in the team or had the quantum expert help them only occasionally, ended up primarily using QBB as a random number generator or simply producing fancy visual effects for the game. This is also evident in projects *QWiz* and *Hamsterwave*: The science experts need to be available and systematically involved in a project aiming towards a citizen science game.

The development of *QWiz* and *Quantum Playground* provided inclusive creative environments for collaborative problem-solving and idea formation throughout the development process and proved to be agile and adaptive processes when dealing with challenges. From the start until the handover of these artefacts, the teams were able to gather together to analyse and adjust the artefacts to suit the design objectives. *QWiz*, in particular, faced multiple small-scale additions to the interface as well as to the functionalities on the back-end and cloud-access, and these challenges were faced through an open and inclusive environment for suggestions. This ensured that these artefacts met the design objectives and were seen as worthy inclusions in an online learning environment. In contrast, *Hamsterwave*'s development was heavily reliant on the short interval provided by the Quantum Game Jam event and the inclusion of the whole team for further development of the game was not possible.

In these interdisciplinary projects, collaborative tasks involve addressing cognitive design challenges. Working closely with practitioners of other disciplines this way offers great learning opportunities. Effective communication is vital not only for learning but also for the successful execution of the project. To analyse these communication dynamics, the meeting notes, personal notes, and the records of the online discussions played a crucial role especially considering that up to five years have passed since the projects were active. These notes helped identify possible communication challenges at different stages and evaluate whether the outcomes have served the original purpose.

These aspects are familiar to anyone working on a multidisciplinary project but have still been the most recurring themes I have encountered among the presented projects. This observation is also supported by multiple other quantum game projects I have either participated in, mentored, or followed. This is mostly due to the fact that most of these projects have been run by first-time quantum game developers. For the projects with experienced quantum game developers, I have witnessed the collaboration between the members to be more inclusive and fluent. I have observed that particularly the people new to such multidisciplinary projects tend to underestimate the value of the other parties. Therefore, the guidelines presented in Chapter 8 serve a purpose for projects of all scales.

## 7.1 Impact

Many of the quantum physics related games have no documentation explaining the possible connections on how certain effects have been designed and executed, nor are they explaining the creative process behind the end result. Transparently sharing design processes enhances the reproducibility of work. Others can recreate or build upon a project with a clear understanding of the decisions made, methodologies employed, and challenges faced.

Quantum game development and interactive art often involve collaboration between designers, developers, physicists, and other specialists. Sharing experiences promotes understanding between disciplines, fostering effective interdisciplinary collaboration. Documentation of design processes serves as educational material for individuals who are not experts in a particular domain. For instance, a designer may gain insights into quantum principles, and a physicist may learn about user experience design, or a physicist starting with their first game project will have a more insightful beginning to their design career. This cross-disciplinary training enhances collaboration and shared understanding.

For the field of quantum game design to grow efficiently, we need to learn from each other also through possible challenges and mistakes made. Documenting both successes and failures contributes to the cumulative knowledge base, allowing for a more nuanced understanding of the evolution of quantum game development and interactive art. Sharing experiences fosters collaboration and knowledge exchange within the community as it enables designers and developers to learn from each other's successes, challenges, and innovations. Therefore by sharing design processes, practitioners contribute to the advancement of the field. Insights gained from previous projects can inspire new ideas and help refine existing methodologies, drive innovation, but also bring insight into projects outside the scope of quantum physics related design processes. This thesis therefore provides insight into the development of future quantum games, quantum art, and science games in general.

Sharing design experiences promotes a culture of inclusivity, where contributions from all team members are valued. It encourages an environment where individuals from diverse backgrounds feel empowered to share their perspectives, fostering a collaborative and innovative atmosphere. Diverse perspectives contribute to creative problem-solving. By learning from the design experiences of individuals from different disciplines, team members can harness the power of diversity to generate innovative solutions and push the boundaries of the project.

Overall, the principles presented here are limited on my personal experiences with the projects discussed and influenced by the specific design objectives. Nevertheless, they also build on an extensive literature review and reflect the years of experience I have had with the design of quantum games. Therefore, these principles may play a vital role in the field of quantum game design by initiating discussions and encouraging critical evaluation of design principles among future quantum game designers.

## 7.2 Challenges and Future Research

One of the main challenges of this thesis is that the gathering of the project data and the interpreting was done in a retrospective manner and is mainly based on the experiences of one person. This aspect was unavoidable, as the motivation for this thesis and the research question arose during the progression of these projects as it became clear also to the author that the development processes of quantum games had not been recorded or made openly available before.

For future research it would be interesting to conduct a more inclusive ethnographic study, which might help understanding the social and cultural context in which these games are being created. The projects presented here represent experiences of Western-world people, but we may see, for example, from the community of Quantum Game Jam developers, that quantum games are being created on every continent [13]. Surveys and questionnaires may reveal more in-depth feedback from the process of developing quantum games, as they may be able to reach a more vast group of people. The extent of this study did not allow for conducting a vast and structured participatory design. The end-user testing was conducted as observation and discussion based format in an opportunistic manner through the projects. Important aspects of quantum game design could in the future be studied by gathering quantitative data on user preferences, satisfaction and other insight from the user perspective.

# CHAPTER 8:

# Guidelines

This chapter provides guidelines for well-established quantum game development through five main design principles that have become prominent for fostering a successful quantum game design in the projects presented in this thesis. These guidelines should be considered as supplementary to existing best practices in game development and serious game development.

Common to all the presented projects has been the inclusion of a numerical simulation of a quantum mechanical system, such as a Bose-Einstein condensate or a quantum walker. In the following, we shall refer to such inclusions as *quantum tools*. The insights gained may therefore be generalised to other simulations or even to the incorporation of quantum computers.

## 8.1 Early Inclusion of Expertise and a Quantum Designer

When the aim of the project is to include a quantum tool, integrate the quantum tool into the design process early on and involve appropriate expertise from the beginning. Therefore, including a *quantum designer* who closely collaborates with the game designer should be a dedicated role in the project. For a small team, this role may coincide with the role of a game designer. This person should possess considerable knowledge of the subject matter and/or the quantum tool to be incorporated into the project. If the designated quantum designer lacks expertise in the specific task, seek external expertise. The quantum designer should have open communication established with the appropriate expert. The quantum designer should be included in iterative meetings among the team with equal presence as the game designer.

## 8.2 Early Design Decision on Quantum Tools

Even an attractive and functioning game cannot, in general, be transformed into a successful citizen science game without the early and full involvement of a researcher expert in the field. The game mechanics and objectives should be directly aligned with scientific research goals, necessitating close communication between the game designer(s) and quantum designer(s) and clearly documented in the game design document or in a separate *quantum design document*. This document should be updated according to the quantum physics or quantum tool-related design decisions and maintained alongside the game design document. Clearly defining the research questions or tasks that players undertake, ensures that their contributions are scientifically valuable. Any proposed changes and suggestions should be communicated to and reviewed by the quantum designer.

Clearly state and justify design decisions regarding the use of the quantum tool in the game design document or the quantum design document. Consult the designated quantum designer for decisions related to the usage of quantum tools or other quantum aspects. This includes aspects such as how a game object interacts with the quantum tool, how the position/colour/speed/etc. of a game object might depend on the quantum tool, or how the output of the quantum tool is otherwise visualised for the player.

Consider providing clear installation instructions of the quantum tool on different platforms and operating systems alongside the project file. This is of particular importance when organising hackathons or game jams where the quantum tool is meant to be integrated into the projects.

## 8.3 Establishing a Visual Language in Team Communication

The visuals used in the introduction of a quantum tool or quantum principles often shape much of the language used during the production phase. The visual representation of quantum physical phenomena and attributes should be prioritised early in the project, to ensure clarity and alignment among team members.

Careful consideration should be given to how theory-side constraints are introduced, ensuring they are appropriate for each stage of involvement and project scope. While simplifications and familiar visual elements may aid in onboarding, they should not hinder or restrict later communication and the creative input. When introducing quantum physics concepts, including the representation of quantum phenomena and quantum tools, tailor explanations to the project's length and phase, and ensure their inclusion in all briefings. The choice of these visual representations significantly influences language and understanding during production. Therefore, avoid relying solely on technical descriptions, as they can create expectations and limit intuitive understanding. Instead, focus on clear, context-appropriate visual representations to enhance comprehension and communication throughout the project.

Simplifications and the use of classical analogies may prove helpful to ensure a quick onboarding, particularly when time is scarce, but might later hinder communication or finding a suitable direction for the design. It should be clear to the quantum expert and quantum designer what aspects of the problem at hand are more crucial for the project outcome and which aspects may be overlooked. When choosing the visual representation for these aspects, symbols and allegories that refer to classical objects and experiences should in particular be carefully considered, and the aspects differing from everyday experiences should be particularly underlined.

## 8.4 Playables and Example Projects

Videos, playable prototypes, and game examples hold significant importance in introducing new quantum tools. Therefore, features of a quantum tool should be presented to the project members through playable prototypes and as an example project, where the tool is readily incorporated into the chosen game engine. Consider providing both successful examples as well as unsuccessful ones with clear commentary on their strengths and weaknesses. Playable prototypes help communicate the desired ways of using the quantum tool and showcase the avoidable means. Playing through this selected array of games will help introduce a new quantum tool and its features to developers, designers, artists, and other roles involved in the project.

An example project, where the quantum tool is deployed with the game engine, should be provided to the developers. This will enable fast onboarding to the project and also help introduce the functionalities and dependencies of the quantum tool. Playable prototypes, screen captures, and videos should accompany the communication throughout the process.

## 8.5 Collaborative inclusion

The collaboration and communication between the developers and science experts should be carefully fostered. The value of the work from either party should not be underestimated but instead equally valued and rewarded. Value each discipline involved in the project and the expertise they bring throughout the project. Encourage an open, inclusive, and supportive decision-making to find innovative solutions for challenges in the development. Offer the opportunity to contribute to the project by a multitude of ways. By including a variety of solution proposals, the project benefits from the very strengths of a multidisciplinary team. The most valuable insight might come from an unexpected direction.

Offer the opportunity to contribute to the project in multiple ways. Foster an inclusive environment where all personalities can thrive, including those who are more calmly tempered, timid, or introverted. Consider implementing text-based communication channels and allowing team members to add to openly shared meeting notes afterwards. Openly shared meeting notes will help keep track of responsibilities within the team and ensures that everyone has a chance to share their insights and ideas, regardless of their communication style.

CHAPTER 9:

# Conclusion

This thesis presents the creative development processes behind five projects and of a simulation tool in the field of quantum physics related interactive art installations and games. It concentrates reporting the design processes behind these projects in a retrospective manner by examining and analysing design diaries, mid-term project reports and recorded text-based conversations. Thus far not many design processes have been reported in the field of quantum physics related user interfaces, software, games or art. Omitting the process behind an artefact and reporting only on the functionalities and use of the artefact neglects also essential aspects that may contribute to efficient communication, process structures or role division. The findings of this thesis promote on

1. Early inclusion of game design expertise and quantum physics expertise,
2. Early design decisions on the inclusion of quantum tools,
3. Establishing a carefully curated visual language for team communication,
4. Using playable prototypes and example projects when introducing new tools to the project and aiding the communication through the development process
5. Collaborative inclusion in multidisciplinary projects.

Here '*quantum tool*´ refers to numerical simulations of quantum physical systems or to the incorporation of quantum computers. It was deemed pivotal that already in the early phases of quantum game development, the usage of quantum physics references or quantum tools were set to the design decisions. The idea of combining quantum physics with games and art is often seen as a challenging task. In 2018, Microsoft and the University of Bristol organised the Quantum Games Ideathon. The winning team was reported to quickly identify what is possibly the most challenging aspect of quantum games:

> *We found it reasonably straightforward to conjure up a concept that either: (a) looked to be fun and engaging; or (b) faithfully represented the underlying quantum mechanics; but not both.*

This perspective has repeatedly been mentioned not just by the people I have been involved with in the projects presented in this thesis, but identified by *Quantum Game Jam* participants earlier as well [12]. Even still, having encountered more than 300 games related to quantum physics [122], and through being a quantum enthusiast myself, I do not second their conjecture; I defy it! Creating a game that both represents quantum mechanics and is enjoyable surely is a challenge, but what better Muse for creativity than a challenge!

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