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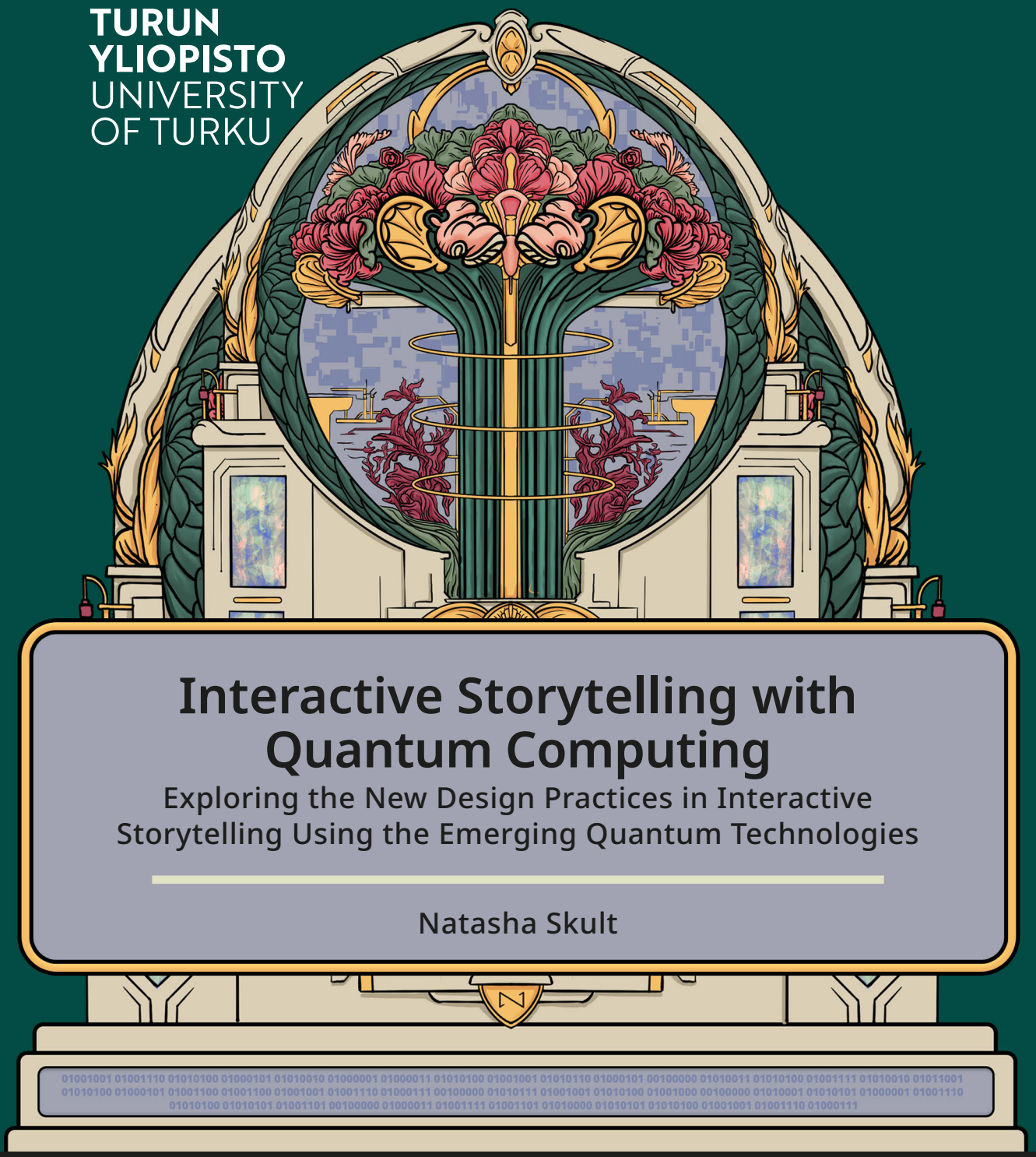

Interactive Storytelling with Quantum Computing

Exploring the New Design Practices in Interactive Storytelling Using the Emerging Quantum Technologies

Natasha Skult

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ABSTRACT

Quantum computing QC is emerging as a transformative technology, yet its implications for game design and interactive storytelling remain largely unexplored within the games industry. This thesis investigates the opportunities and challenges of integrating QC into interactive media, in particular games, with the focus on its impact on game design methodologies, narrative structures, and user experience.

Through a game design perspective, this thesis examines: (1) the concrete pros and cons of using quantum over classical computing in interactive media, (2) how QC challenges the role of game designers and established best practices, and (3) how user experience differs when engaging with quantum-enhanced storytelling. The study explores current applications of quantum mechanics in game development, AI-driven narrative techniques, and new design methodologies tailored for QC-based experiences. Case studies include C.L.A.Y – The Last Redemption, QWiz, and QPlayground, which offer insights into both designer and player perspectives, highlighting challenges such as predicting user interaction on future QC platforms and adapting design workflows to the principles of quantum computing.

By synthesizing findings from interactive media, QC simulations, and player experiences, this thesis proposes a clear set of guidelines for game designers and quantum physicists as industry professionals, as well as academic researchers, to utilize in designing interactive storytelling experiences with quantum computing. The results provide a foundation for future explorations into how QC can redefine immersion, procedural generation, and player engagement in next-generation game design practices.

KEYWORDS: game design, interactive storytelling, narrative design, quantum computing, quantum games, user experience, cross-platform development, gamification, visualization, game jams

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TIIVISTELMÄ

Kvanttilaskenta (*quantum computing*, QC) on nousemassa transformatiiviseksi teknologiaksi, mutta sen vaikutukset pelien suunnitteluun ja interaktiiviseen tarinankerrontaan ovat jääneet suurelta osin tutkimatta peliteollisuudessa. Tässä opinnäytetyössä tarkastellaan kvanttilaskennan integroinnin mahdollisuuksia ja haasteita interaktiiviseen mediaan tietyissä peleissä keskittyen sen vaikutuksiin pelien suunnittelumenetelmiin, kerrontarakenteisiin ja käyttökokemukseen.

Pelisuunnittelun näkökulmasta tämä tutkimus tarkastelee: (1) kvanttilaskennan käytön konkreettisia etuja ja haittoja verrattuna klassiseen tietotekniikkaan interaktiivisessa mediassa, (2) kuinka kvanttilaskennan haastaa pelisuunnittelijoiden roolin ja vakiintuneet parhaat käytännöt, ja (3) kuinka käyttäjäkokemus eroaa kvanttitehostetussa tarinankerronnassa. Tutkimus selvitää kvanttimekaniikan nykyisiä sovelluksia pelien kehityksessä, tekoälypohjaisia narratiivitekniikoita ja uusia suunnittelumenetelmiä, jotka on räätälöity QC-pohjaisiin kokemuksiin. Tapaustutkimukset ovat mm. peleistä C.L.A.Y – The Last Redemption, QWiz ja QPlayground, jotka tarjoavat näkemyksiä sekä suunnittelijoiden että pelaajien näkökulmista ja tuovat esiin haasteita, kuten käyttäjien vuorovaikutuksen ennustamisen tulevilla QC-alustoilla ja suunnittelutyönkulkujen mukauttamista kvanttilaskennan periaatteisiin.

Syntetisoimalla vuorovaikutteisen median, QC-simulaatioiden ja pelaajien kokemuksista saatuja tuloksia, tämä tutkimus ehdottaa pelisuunnittelijoille ja kvanttifyysikoille alan ammattilaisina sekä akateemisille tutkijoille selkeää ohjetta, jota voidaan hyödyntää suunniteltaessa interaktiivisia tarinankerrontakokemuksia kvanttilaskentaan. Tulokset tarjoavat perustan tuleville tutkimuksille siitä, kuinka QC voi määritellä uudelleen immersion, prosessien luomisen ja pelaajien sitoutumisen seuraavan sukupolven pelien suunnittelukäytäntöihin.

ASIASANAT: pelisuunnittelu, interaktiivinen tarinankerronta, narratiivinen suunnittelu, kvanttilaskenta, kvanttipelit, käyttäjäkokemus, monialustakehitys, pelillistäminen, visualisointi, pelijamit

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Tawia, a fellow game industry professional and academic with whom I have had the privilege to build a game design and development program at Ashesi University in Ghana in 2023, as the first of its kind on the African continent. Eyram, you are a true inspiration and I am looking forward to all the future opportunities we will be building together for the next generation of game industry professionals!

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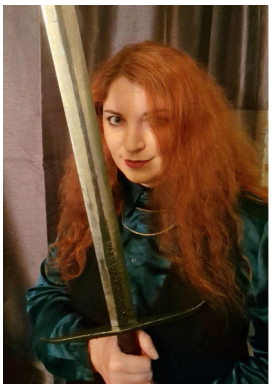
10.03.2026
Natasha Skult



NATASHA SKULT

Natasha Skult is the CEO and Creative Director of Mi-Tale, a game and software development company from Finland, focusing on interactive storytelling and narrative-driven experiences in games and gamification. She is an active member of the Finnish and international games industry with many roles and activities, including being a Board Member of IGDA Foundation and Lead Organizer of W Love Games Conference and Finnish Games Week. Throughout her 15+ years of career in game industry and academia, she has been establishing and building cross-borders programs for business and cross-cultural regional developments with emphasis on utilizing local talents and expertise. Besides industry work, she is also active in academic research exceptional interest in the topics of game design and interactive storytelling using quantum computing, and teaching courses in game design, gamification and game (digital) art production at University of Turku in Finland and Ashesi University in Ghana.

Table of Contents

Abbreviations

UI	User interface
UX	User experience
QC	Quantum computing
QT	Quantum technology
GQGJ	Global Quantum Game Jam
QGJ	Quantum Game Jam
VR	Virtual reality
AR	Augmented reality
XR	Extended reality
NPC	Non-player character
AI	Artificial intelligence
LLM	Large language model
RPG	Role playing game
R & D	Research and development
SDK	Software development kit
API	Application programming interface

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Bulatovic Trygg, N., Skult, P., Smed, J. 2018. Narrative Design. In: Lee, N. (eds) Encyclopedia of Computer Graphics and Games. Springer Cham, 1225-1230.

https://doi.org/10.1007/978-3-319-08234-9_140-1

II Skult, N., Smed, J. 2022. The Marriage of Quantum Computing and Interactive Storytelling. Games and Narrative: Theory and Practice, Springer Cham, 191-206.

http://dx.doi.org/10.1007/978-3-030-81538-7_13

III Skult, N., Piispanen, L., Smed, J. 2025. Exploring Interactive Storytelling in Virtual Reality for Teaching Quantum Physics and Computation: A Comparative Analysis of Qwiz and Qplayground. In: Cordan, Ö., Berkman, M.I., Dincay, D.A., Catak, G. (eds) Extended Realities, Virtual Environment, and Interactive Experiences. CRC Press, Taylor & Francis Group, 60-80 .

https://doi.org/10.1201/9781003581642

IV Skult, N., Piispanen, L., Atas, M., Jankiewicz, K., Surer, E., Smed, J., & Seskir, Z. C. (2024). A Chronicle of Quantum Technologies in Game and Software Development. IEEE Computer Graphics and Applications, 44(5), 14-26.

https://doi.org/10.1109/MCG.2024.3448613

V Skult, N., Koporcic, N. (2024). Nurturing sustainable growth in a competitive market : Case study of MiTale. Individuals in B2B Marketing : Sensemaking and Action in Context. Routledge Studies in Marketing, 235-249.

https://doi.org/10.4324/9781003388036-16

1 Introduction

From the warmth of the first campfire to the digital age of interactive media, storytelling has always been a fundamental feature of human evolution, continuously adapting and reflecting our eternal desire to connect, imagine, and explore. The ability to shape the narrative became a craft, and with the skill to record the stories, the narratives transcended time and place and shaped civilizations. As a visual storyteller, a game developer, and an experience designer, I have been privileged to start training my craft from an early age through traditional art mediums and enhancing the skills with the technological advancements in digital art production. Fascinated by the wide range of visual storytelling methods, to which theories of semiotics have had a huge influence in my academic research journey, I aimed to seek possible new avenues for the next generation of narrative design practices, enhanced by the emerging technologies such as quantum computing. One may ask: "What does quantum computing have to do with storytelling?", and at the first glance it may sound like a strange match, but there is an ignited spark between them that may open new possibilities for the narrative and experience/game designers to explore. In this dissertation, I share a selected set of case studies, published articles and book chapters on these topics, along with the challenges and possible next steps for further inquiry.

Throughout my research I have been focusing on the interactive storytelling practices in games, including gamification, serious games and entertainment games. Games as an artform and the media of expression allow us to address and experiment with different aspects of design practices as well as technological implementations, especially using the emerging technologies for which no best practices are set yet. The game industry is one of the fastest growing industries that encompasses all types of media and platform distributions [1; 2]. We have games made for almost every digital device known to human society, from oscilloscopes to self-driving cars [3]. As game technology is adoptable and able to create interactive experiences for cross-platform development, it allows us to do thorough experimenting and analysis of various design features and technical capabilities, even with the emerging technologies such as quantum computing. Game environments are built to be safe and engaging spaces for their users [3], whose behaviour can be tracked and recorded.

Such data allows observers (designers, developers and researchers) to analyse and learn about different user behaviours based on the specific parameters within the observed game setting [4; 5]. By studying the variety of behavioural patterns,

designers can create more immersive experiences and incorporate a variety of accessibility features [6]. According to Seskir, game-based environments are often used for onboarding complex topics in science, engineering, healthcare, and other fields, for both professional staff and their clients. Furthermore, science-based games can achieve a variety of goals for education and research purposes, as well as effective outreach and public engagement, making them four out of five "Q-12 Education Partnership's QuanTime K-12" classroom activities in engaging teachers and students [7]. In these learning environments we can create custom experiences based on individual needs and preferences, and the data collected from their interactions can be used to further improve the design practices as well as research methods. In this section, I will introduce the research motivations, objectives and research questions, and the structure of the thesis.

1.1 Research Motivations on Interactive Storytelling with Quantum Computing

In the digital world, interactive storytelling is a vast discipline that plays a significant role in modern communication and data management. The practices are widely used in multiple industries, from marketing and PR to software and game development, requiring a multidisciplinary approach in interaction design, platform choice(s), and accessibility in receiving, comprehending and interacting in a meaningful way with the given content. In this thesis, my goal was to explore the current best practices in interactive storytelling with the latest available technologies, and their performance with quantum computing specific requirements [8].

Quantum computing is an advanced technology built on radically new forms of software and hardware, yet in practice used in a hybrid model with classical computing [9]. The unique principles of QC introduce multiple elements that can benefit the game design processes, especially in exploring new ways of designer-player interactions and their specific roles. To illustrate these opportunities in game design shifts, I use my own practical experiences of creating games with quantum numerical simulations and reflect on how I approached the challenges that emerged in the process, especially using Qiskit by IBM [10].

As a visual storyteller, a game developer, and experience designer – my goal was to utilise the acquired expertise in these fields and provide a new view to the interactive storytelling design practices. The case studies used in this thesis are carefully selected to adhere to the interactive storytelling systems and techniques based on the specific software development conditions, providing better understanding of the current and next generation of design challenges, as well as the opportunities that QC has to offer to the new age of interactive storytelling as a discipline.

The primary goal of this study is to examine the effect of the emerging technologies, in particular use of QC, on directions of interaction, experience and storytelling

design practices. As a result of this thesis, the specialisation holds both theoretical and applied research aspects, providing a research and development toolkit for aspiring game designers and developers. With this thesis, my aim was to demystify the use of quantum computing in games, in particular use of QC as an adjunct tool for game designers. The technological advancements of quantum computing allow not for just an increase of the computational capacity and speed available for game developers, but more environmentally friendly choices in energy consumption in development [11]. Moreover, the main impact of this study can lead other researchers to discovering new application areas for utilising the quantum technologies in comparison where it is currently used.

The main motivations behind my research started through the collaboration with quantum physicists working on gamification projects, which allowed me to get familiar with the quantum simulation and computation principles along with the common methods of their implementation in other types of media, such as art installations, music composing, and games. As a game designer by profession, the most interesting approach to quantum technology is treating it as a potential tool that could serve my work towards enhancing the players' experiences in possibly novel ways. This does not mean that I see the use of quantum technology enhancing the player's gameplay per se, instead supporting our craft of game design in providing valuable experiences for the players within the gameworld, and possibly different methods of exploration. Just as any other tool, I approach quantum computing as such – a new tool in my game design toolbox, a new brush to my palette. It is not a solution to any design challenge at hand because in user-centered design, users are the ones that dictate the pace of the experiences, while we via our tools provide the building blocks. In the current state of generative AI tools on the market and early attempts at fully-AI generated games, we can already observe the users' mixed opinions and unmet expectations [12]. Therefore, I see no scenario in which quantum computing creates a game instead of a game development team but instead provides more opportunities for developers and game designers to work towards serving the players in the best way possible, and in addition ease some technical challenges such as computational speed and optimization.

1.2 Objectives and Research Questions

The key objectives of this thesis explore the integration of QC into interactive storytelling and game design. The primary aim is to evaluate the advantages and challenges of using QC over classical computing in the development of interactive media, particularly focusing on its impact on game design methodologies, narrative structures, and user experience. Additionally, this thesis examines how QC challenges and reshapes the role of game designers, influencing their workflows and best practices in interactive storytelling. Another core objective is to investigate how the user expe-

rience differs when interacting with quantum-enhanced versus classical storytelling, specifically how players' awareness of QC influences their engagement. Finally, this study aimed to develop a comprehensive toolkit for game designers, providing them with the tools to effectively integrate QC into the design of interactive storytelling experiencesTo achieve this, games as an artform and the craft of making gamified experiences are the core principles to begin this investigation. By several definitions, games are closed systems that hold carefully designed structures and means of interaction, which is an excellent environment to do the required experiments and collect both qualitative and quantitative user experience data [4]. In addition to being safe digital environments for trial and error, within the same game system we are able to change the parameters within the gameworld as required by the research questions and make comparisons, which helps us make more accurate data measurements of the user experiences. For this thesis, I have selected three main research questions which are covering some additional topics as follows:

RQ1: What are concrete pros and cons of using quantum over classical computing in developing interactive media (e.g. games)?

Research topics:

1. QC – current use in game development: interaction design, interactive storytelling (narrative design and experience design methods), game design
2. Use of quantum mechanics – as an inspiration, in a simulation (use of simulators), partial implementation with QC (e.g. system is directly using quantum computation for a set duration of time) and full QC integration
3. The role of AI and machine learning in interactive storytelling using QC – challenges in accurately modelling players, accommodating diverse playstyles and player-motivations as well as managing procedurally generated content

RQ2: How does emerging technology such as QC affect/challenge the role and methodologies of the game designer and the established best practices in game design?

Research topics:

1. Role and skill set of the designer – how does QC reshape the role of the game and narrative designer?
2. Conventional vs required interactive storytelling systems
3. Proposal of design methods when using QC in interactive storytelling
4. Designing experience using quantum simulation vs. real quantum computing – challenges and opportunities by analysis of the case studies: C.L.A.Y

– The Last Redemption (commercial RPG), QWiz (VR gamification project) and QPlayground (VR interactive experience)

RQ3: How does the user experience defer between using quantum over classical computing in interactive storytelling?

Research topics:

1. Chronotope for interactive storytelling overview – examining the engagement and user experience effects by time and place between designer and a player, highlighting the dynamic between designer's original intention and the user's later experience, often mediated by emulators or simulators.

2. Time and place presented inside of the immersive experience (the role of time and place in narrative design) – player centric design process for the engaging experience

3. Developing the content before the platform is available – predicting the behaviour of the users (next generation of platforms such as quantum computers, e.g. game consoles)

Based on this set of research questions and topics, my work has focused on the role of a game designer, as in *how* and in *which aspects*, QC can improve the design practices, user experience or possibly ease the game development with its technical advancements. To achieve this, I have divided the scope of the thesis on three main subjects:

1. Narrative and game design practices

2. Technical implementation of game development tools with quantum technologies (mainly numerical simulations)

3. User-centered design practices

While I have published more articles on these topics, this thesis is a collection of four selected publications which address the research questions, with an additional supporting publication, that together provide key elements to consider for the future research of this topic as well as the game industry professionals in utilizing the quantum technologies in commercial games.

1.3 Structure of the Thesis

In the following sections, I will be sharing the research methods and results of the project – starting with storytelling principles in interactive media, such as games (Section 2), followed by the introduction to quantum games and the practical use

of quantum technologies in game design and cross-platform development, including case studies from commercial entertainment games and gamified solutions in education (Section 3). The discussion continuous with the selected publications summaries (Section 4) and the results of my research work, which includes a reflection on the importance of the project development processes, teamwork and communication when working with cross-disciplinary products and services, as well as the importance of the community-driven efforts in research and development innovations. To complete the remarks of this thesis, I will present concrete results and the next steps in this area of studies, along with the discussion on the possible continuation of this study (Section 5), followed by the conclusion (Section 6).

2 Foundation – The Craft of Interactive Storytelling

Stories have an incredible impact on us as conscious beings, and what makes the notion of storytelling most fascinating are the communication principles which allow us to share and more importantly *comprehend* the shared story. The key principle of communication is the exchange of *meaning*. These two terms: comprehension and meaning, are the leading subjects of *semiotics* [13]. Semiotics is the study of signs and symbols and their use or interpretation, making it the fundamental agent in assessing contextual implications across languages and cultures. It explores how meaning is created and communicated through spoken and written languages, visual sources such as images, gestures, objects, and other forms of representation. The study of semiotics is as many other studies originating in Ancient Greek philosophy, but it took its own route in linguistics, especially in the works of Ferdinand de Saussure [14] as well as philosophy, from the work of Charles Sanders Peirce [15].

In its core, semiotics is the study of signs, where the sign can be defined by anything that can communicate intentional or unintentional meaning or feelings to the one observing/receiving/interacting with the given sign [16]. The core of the semiotic process is in the relationships between signifier (the form that the sign takes, e.g. a word, image, or sound), signified (the concept or idea the sign represents) and interpretant (how the sign is understood or interpreted by an individual/audience). Here communication involves the process of encoding, transmitting, decoding, and understanding messages between a sender and a receiver, with the goal of achieving mutual understanding. At its core, communication is about creating shared understanding to build relationships, solve problems, and achieve goals. To have effective or successful communication between parties, it is necessary to have:

- Clarity of the message where we must ensure the content is understandable to the targeted audience
- Contextual relevance since the context of the message has a major role in having a successful communication, tailoring the message to the cultural, social, and situational context
- Active feedback allows us to collect and analyze the responses in order to confirm understanding and refine the message

- Empathy and intent are possibly the most delicate parts of communication, where we consider the emotions, perspectives, and needs of others to foster the intended connection

When we lay down these terms and practices of semiotics, one can easily recognize the shared principles with computational systems and communications [17; 18]. In addition, when a game designer is making a game, the main set of tasks is to create a game system with clear goals, rules and a set of actions/reactions to empower players' immersive behavior that allows them to face the given challenges and ability to solve them intuitively. This means that we have a task to design the experience (hence why I often refer to game design as experience design throughout my work in both game industry and academia) and communicate all aspects of the world, the characters, the challenges and tasks along with the methods of achieving the set goals to the players. To achieve this, we need to make sure that the game system, which is built by code and audio-visual assets, is properly set for the platform upon which the game is being played (technical compatibility for system to understand players' inputs). This way we communicate with the players in a coherent way with the preference of enhancing the *feeling of free choice* and intuitive gameplay experience. From choice-based to open-world games and across the genres, most games have very carefully designed systems in place that allow players to feel their choices make an impact on the gameplay, but the truth is that all gameplay aspects are designed with a set of distinct choices by the developers every step of the way. Even in creative gameplay like Minecraft[1], the set rules of the world allow specific actions that enhance the feeling of freedom within the gameworld, but if you properly analyze it, the world functions within its own set of rules that have its own set of limitations. The more the players say that they feel "free" and "my gameplay choices make a difference" in the gameplay experience, the more present the player agency is [19]. The true power of game design as an artform is the ability to give players emotional connection through interaction, which creates the experiences and translates into personally meaningful memories.

This suggests that *communication* is a leading principle of game design, which for digital games is based through set of *computational communication* between the gaming device (a machine) and the user, as well as between a machine with another machine. Unlike living organisms, computers are built with transistors, which have a simple yet vital role of being on/off switches [20]. Communication happens when the transistors are interconnected and form logic gates. Each of the gates has a specific set of tasks that calculates deterministic binary functions of the input signals that then appear in its output signal. That output signal is then sent to the input of one or more logic gates. This makes the whole structure of the computational system static, which is incredibly beneficial for the users and allowed the fast technological and

[1] Minecraft by Mojang AB, Microsoft Corporation: https://www.minecraft.net/en-us

empirical developments in recent human history. The fact that computers can repeat the same functions (if needed endlessly) as required, is what makes them reliable. We can produce the expected results of the assigned tasks with quality repeatedly. In addition, I wish to add that there is a clear division between hardware (the physical components of the device), the software (information) and the power supply (energy) of the computers, which enables us to tune different aspects of the computational features based on the specific needs of the user.

In nature, we do not have a clear division between the hardware (body), the software (knowledge, e.g. DNA) and power supply, as all these are interconnected and function inseparable as one entity – a living organism. These interconnected functions upon which the whole universe operates, according to our current understanding of science, are based on the principles of quantum mechanics [7]. The computer cannot repair itself, transform matter into energy or build a copy of itself as any living cell can. Instead, computers perform specific functions that they clearly understand based on the way they are built and the algorithms that are stored in memory. Any aspect of production in which intuition, creativity and understanding of signs is required outside of the data upon which the provided system is trained upon, the computer fails to understand/perform. Only the instructions that are already in its memory can be performed, while inputs from the environment cannot be understood. This is why even the latest developments of artificial intelligence (AI), and machine learning cannot understand and perform the tasks as a human would, since it does not have the intuition and consciousness to do so with its own will [21]. For creating any type of high-performing AI systems, it is necessary to have an incredibly vast amount of data in the computer memory from which it can use the acquired knowledge and based on only such information, perform/predict/function as requested, but it cannot understand the performed action by itself. Why is this important to address in interactive storytelling? As already stated above – communication with the user who can receive and comprehend the message given, is the key element of interaction design and narrative experiences.

2.1 Brief Introduction to Game Design Principles

Game design is about solving challenges and making different parts of the jigsaw puzzle work together and fit even though some pieces might have an extra edge. With over a decade of professional experience in game design, I must admit that solving such challenges is the most fascinating part of our craft. When you design your own game, the most common challenges are to keep reasonable scope, to have accessible and relatable gameplay experience for the players, and make sure the game is enjoyable and possible to complete. However, when working on someone else's game or a vision of utilizing game design principles or technologies, commonly the parties involved in such a project are not necessarily familiar with the game design

and development practices. Such matters are easily solved with communication, but the project vision, the goals and set boundaries of it, especially in the case of designing serious games and gamified solutions, is where the game design becomes an artistry. Not many game designers share my passion for working on gamification design, and I do understand their reasons, but what I find extremely valuable is the amount of learning and innovation that happens in the least expected ways and my overall game designer's skillset. As an example, the challenges for a game designer in developing gamification project can be, but are not restricted to:

- *Goals of the project.* Most of the serious games and gamified solutions have very precise goals they need to achieve with their target users/clients. Regardless of the field or discipline for which gamification has been developed for (e.g. education, healthcare, infrastructure), each project has a unique set of parameters which is not applicable even to similar projects on the market, since the target audience can be different, the platform of distribution can be changed or the professionals utilizing the solution with their clients have additional needs to be addressed within the design. This also reflects knowing and understanding the final user/audience – *who are you making this product for*? Is it the professional who ordered the product or their clients who should be the main users? Defining and clarifying these matters with the professionals you work with is crucial, because they might give feedback based on their expertise, yet forget that they are not the target audience – their clients are. It is game designers' task to make sure every product is user-centric and that we address the needs and expectations of the users. Unlike in developing entertainment games, where developers can perform the game testing with target audience at any point of the development cycle, in gamification the testing might not be possible to perform by developers but by a third party, whose collected data might not address all the aspects designer would wish to analyze.

- *Users.* Understanding what users' expectations, needs and wishes may be in interaction with this type of solution. In my experience, fast prototyping and testing with the users have yielded the best results, but there is a high probability that such an approach might not necessarily be possible depending on the project specifications and setting. In such cases, I recommend gathering data from the professionals working with the target users and understanding how their process works, which can solve both design and technical challenges in later stages of the development process. In addition, understanding what type of surroundings and conditions the user is in when interacting with the solution is vital, since a different design approach is needed when creating a solution for a closed and observed environment guided by a professional than for a free time activity in users' leisure time. Each of these aspects will have a huge impact in understanding the needs of the users.

- *Too big a scope.* As mentioned, professionals of different disciplines might not be familiar with game development practices, which might cause higher expectations of what it is possible to make within the presented specifications of the project, including the number and type of distribution platforms. To accommodate the expectations and create a high-quality product, game designers must set the pillars of the project that would allow the project to evolve and expand in content gradually, making sure that the core elements and features of the solution are intact and have an achievable scope. All additional features would be treated in a modular manner that can be developed as the project specifications and needs allow.

- *Maintenance.* Yet another big challenge that quite often is not thought of at the start of the project but definitely should be - who will be making sure that the gamified solution is maintained for the users once the project is launched? We can observe countless projects being removed every year from distribution platforms, simply because they do not have the legal documentation updated according to the latest terms and regulations, and in addition the technical requirements that might need to be updated based on the platforms' technical upkeep. The majority of the gamified R&D projects do not have maintenance set in place, and once the project is completed no party takes responsibility for its upkeep.

The game designer is the one who should find the solutions for such (and many other) types of challenges that different projects in gamification may present. In my opinion, designing gamified solutions will train a game design professional better than any other design task or a challenge because you need to solve the practical, technical, goals-set and user-focused aspects of the project while making it engaging, meaningful and fun for the user to interact with and keep motivated to continue its use. Training to transform non-engaging topics that are not typically considered "fun" into enjoyable and meaningful experiences, is the ultimate game design challenge, which is how we get to properly challenge the skill set and craft as professional game designers.

2.2 Brief Introduction to Narrative Design Principles

The narrative design as a topic in my thesis is presented in Publication I. Since the article was published, there have been significant changes in the best practices of interactive storytelling design, therefore I wish to expand the results of it with more recent developments in this field.

Interactivity is the key difference between games and other forms of media, where an essential part of experiencing the story happens through a direct participation with the narrative progression. In traditional storytelling, the flow of the story

is linear with a clear stream from the author to the audience. In interactive storytelling, the audience plays an active part in shaping up the story and co-creating it with the author [22]. In addition to the act of interaction with the given medium, the emotional connection that player establishes with the content comes through cross-pollinated sensory communication, especially in audio-visual-story-driven environments of interaction. To perceive and understand the message from the gameworld, the experience of the player mainly happens within themselves by series of conscious and nonconscious responses to the actions, decisions and reactions of the player. The *meaningful experience* comes from the successfully delivered message through a set of signs that player can interact with, governed by contextual relevance and intent. The role and responsibility to design such experiences for the players belongs to a narrative designer.

A narrative designer is not a writer, and the narrative designer does not usually write the story for a game (yes, these two tasks can be given to one person to manage within the team, but what is important to address is that these are not the same task to begin with - narrative design comes first, the writing comes later). The main role of a narrative design is to make sure that the game design principles (from the overall game design to the smallest features within level design, in-game economy, difficulty levels, accessibility etc.) are followed and logically connected between different mechanics and aspects of the game, into a coherent gameplay experience. In the current game industry practice, the narrative designer tackles the necessary choices of where to place different types of events as smaller or bigger reveals to the player (e.g. story bits, additional gameplay), connecting the mechanical and aesthetic choices which provide reasons/meaning for the player to keep playing. Once the narrative systems are in place, narrative designer provides the specifications to the rest of the creative team of what type of interactive storytelling will be needed for the overall experience. Some story parts can be purely audio-visual, some textual with possible voice-over features, some can even be content provided by the players themselves.

Narrative brings the answers to “why” something is the way it is within the game and should be included in the game design process as early as possible. Setting narrative pillars along with the game design pillars [23] can prevent feature creeps, overcome game design challenges and even help with setting the aesthetics of the game. The sooner narrative structures are in place, the sooner game concepts can be tested and prototyped. This enables faster feedback loops from the players or business partners, as well as faster iterations in the game design cycles. Regardless of the storytelling principles you might decide to have in your game, the most important part is to have a user-centered approach with clear messaging and relevance to the audience you aim to reach.

2.3 Procedural Storytelling in Game Design and the Use of Emerging AI Tools

In recent years procedural storytelling in game design has been a more prominent choice for game developers to tackle challenges of content optimization, player agency and replayability [24]. It is a narrative design method in which narratives are created dynamically, usually through the systems that respond to the player actions and in-game events as they are triggered instead of pre-scripted content. A crucial factor in designing dynamic and immersive gameplay experiences is in increasing the replayability value of a game. There are several principles upon which procedural storytelling allows more prominent "dialogue" between a designer and a player [25]. By merging player agency, dynamic systems, contextual feedback, dynamic characters and in-game relationships, emotionally engaging and meaningful choices, it enables the gameplay to feel deeply personal for each individual player. However, procedural game design is not randomized content given to the players, it is a carefully designed system governed by consistent rules, which can be found within interconnected systems such as behavior of non-playable characters (NPCs), world generation, event triggering system, resource mechanics etc. The game content is not necessarily generated by the AI systems, but the content design has modular principles that allow dynamic interaction by the player which ensures that events feel relevant to the given setting. This narrative design approach allows for addressing different player types, catering to different playstyles and player motivations. In addition, some parts of the design can still include partially or fully user-generated content, depending on the type of systems one wishes to include in their game design.

With the rise of AI tools in the current market, there is of course big debate on AI-generated content regarding ethics, IP rights, and most importantly player perception. AI tools have always been a part of the games industry, but used as internal solutions by the teams, creating their own AI tools based on their team's needs and the type of games they would be making. Automation, optimization and ease of production cycles have been in game development practice for decades. While generative AI tools (large language models – LLMs and diffusion models) available on the market are being developed with high efficiency and speed, the legal practices and policies in using the AI generated content are not yet defined nor unified. We observe that many businesses see great potential in utilizing AI tools in content creation, enabling automation of certain development tasks, optimizing the game performance, faster content creation and distribution. However, with the high risks at hand in commercial use of the AI generated content, it is not wise to use them in other ways than as moodboards, conceptualization, ideation and brainstorming tools by professionals. Here are some of the most common risks to be aware of in using the generated AI content in your commercial product in the current market:

1. *Ethical concerns.* Content produced by an LLM tool is based on datasets

where we do not necessarily know their origins and if the art used for training is given by consent with adequate compensation to the author of the original artwork. In addition, AI tools may generate content that can be offensive for different groups of people, based on ethnic, religious or other identities, reinforcing harmful stereotypes. As the datasets grow by also including AI generated content within their own systems, it can start creating repetitive and degenerated content.

2. *Third party content creation.* Who owns the AI generated content? Clarifying who has intellectual property rights, which are essential for product ownership and additional business opportunities such as licensing. At this moment, by majority of worldwide laws, the AI generated content belongs to the public domain[2]. That means that as a "creator" of your game that has AI content developed by 3rd party AI tools, you have no ownership rights to the characters and assets in your game. As mentioned, regulations and policies are developing slower than the AI tools, which means that even in the near future this setting will not be relevant, and we do not know what rights will be assigned and to whom - will the company who owns the AI tool have full IP rights for the content created by them, and will they ask for the revenue share of your game as you used their tool in game production and distribution? Time will tell.

3. *Lack of creative freedom and predictability.* You have no control over the type of content that an AI tool will generate, and it is unpredictable. With the current AI tools available on the market, both free and paid services, the content that may require specific features and details are not possible to achieve as they are based on the specific datasets available in their systems. Even if you provide your own samples and materials, it will not produce the new version but rather cannibalize the provided material and add it to the existing datasets which do not provide the good quality content that your players would be expecting.

4. *Players.* Do not underestimate the needs, wishes and expectations of the players! Games are an artform and with the industry rapidly growing year after year, we have massive amounts of player data across all possible platforms, showing us the various levels of player expectations when picking the games they wish to play. From the level of quality in experience design, to gameplay controls, accessibility, representation and overall "fun" elements that games provide, there might be a backlash from the player communities in having AI-generated games. It is too early to say, but one thing that game designers

[2] European Union Artificial Intelligence Act
https://www.europarl.europa.eu/thinktank/en/document/EPRS$_BRI(2021)698792$

always follow is user-centered design principles, which current AI tools are not able to provide.

In my opinion, based on experience as a game industry professional, we all must become AI-literate, which refers to both technical skill and methods of its use – being aware of where, how and with what specific purpose the AI generated content would be made for or possibly distributed commercially. We already have games that use AI generated content and one with more traction is "1001 Nights" game by Ada Eden, which originates from the academic research project [12]. While we are still in the early stages of fully integrating AI tools made by third party providers, game companies commonly have their own set of AI tools that are made by teams internally, and without doubt these tools have no risks to continue using and improving. No developers should be replaced by AI tools, on the contrary the tools should primarily increase productivity and ease the workload, which should be the main purpose of such tools.

Besides AI, there have been significant developments in other fields, including quantum computing, which is an emerging approach to computation that uses principles of quantum mechanics. There are multiple ways in which quantum and classical computers differ from one another, and in the next section I will be continuing the discussion on interactive storytelling and game design principles but utilizing the quantum technologies. Furthermore, I will also summarize the best practices I have discovered by working with quantum-classical-hybrid implementation in game development as a game designer and an art director.

3 Quantum Technologies and Games

With this thesis, my set goal was to demystify the use of quantum computing in game design and development, in particular use of QC as an agile tool for game designers. The technological advancements of QC allow not just the increase of the computational capacity and speed for the game developers, but more environmentally ethical choices in energy consumption in developing and distributing the games [7]. Moreover, the main impact of this study was to discover new application areas in game design utilizing quantum technologies, focusing on the area of interactive storytelling. As a result, this thesis includes three selected publications which present three different case studies in bridging quantum technologies and game design, describing the processes, challenges and possible new avenues for further research and development in this field. In this section I wish to summarize the results, learnings and provide a proposal for the next steps for quantum and classical software developers to consider in their research or development work.

The selected case studies belong to different genres of games and gamified solutions, targeting different types of audiences and platforms of distribution, including cross-platform solutions. Each of these projects have a unique approach to the implementation processes of quantum technologies based on the specific requirements and needs of the projects, with focus on the respective target audiences for each product. The practices and development choices made in each project that are described in the published work serve as a showcase of what practices worked (or not) in that particular setting based on numerous project-specific restrictions, scope and end goals. These serve as possible practices to consider when starting with quantum-classical hybrid computing [26], or if needed as an inspiration for developers and scholars alike to pursue their cross-platform endeavors.

3.1 The Initial Spark

In Publication II the article describes the experiments done on the commercial game C.L.A.Y. - The Last Redemption (see Fig. 1) by MiTale[1]. As a creative lead and a co-designer of the project, I was fortunate to have Dr. James Wootton (IBM) visiting our office in 2019 in conjunction with collaboration on projects with Prof. Sabrina

[1] MiTale Ltd – an independent game development company from Turku, Finland. Established in 2017, https://www.mitale.fi/

Maniscalco and her research team. Dr. Wootton had at the time been working on procedural generation using quantum computing (Qiskit[2]) and he demonstrated its applications in the environment of Minecraft Education[3] [27].

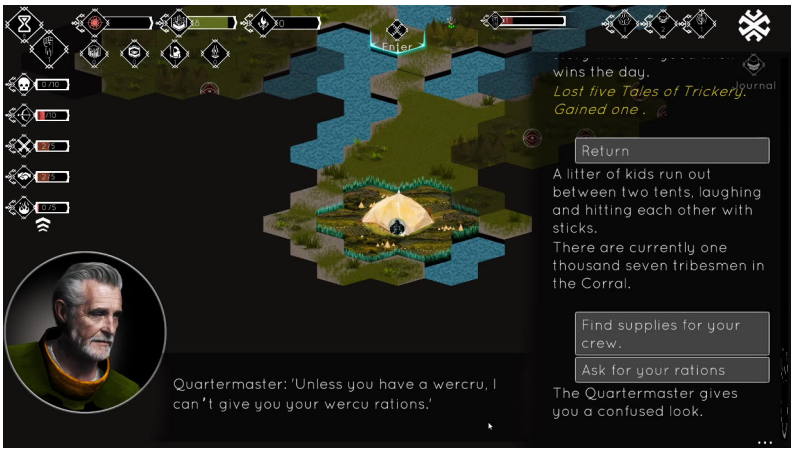


Figure 1. C.L.A.Y. – The Last Redemption, gameplay screenshot

I found the principles he used applicable in C.L.A.Y. - The Last Redemption, our own narrative-driven game which was in the early stages of development. I have presented the project to Dr. Wootton and shared my ideas of which game design aspects I would like to test with his new discoveries. We started brainstorming if Qiskit could be integrated with the narrative design and the systems we have been developing for our games in general, as MiTale studio focuses on creating narrative-driven role-playing games (RPGs) for PC and consoles. Our team of developers already have experience of using Qiskit and other quantum numerical simulations, in addition to creating a custom-made plugin for Unity3D[4] to be used at game jams and hackathons for those who would be interested in testing these solutions.

At the time, IBM's development efforts for Qiskit[5] were focused on quantum circuit building, simulators, and cloud integration. There were not yet sophisticated and publicly available repositories or plugins that would enable direct integration with any of the game engines on the market. As a result, our team had to develop a custom Qiskit integration system reflecting the specific needs of the game. We used similar architectural approach to contemporary ones, using a Python-based SDK backend running on a local server combined with C#-based frontend implemented in Unity. The Python API (application programming interface) of Qiskit would have a selected subset of algorithms from available libraries for us to establish a connec-

[2]Qiskit by IBM https://www.ibm.com/quantum/qiskit

[3]Minecraft Education by Mojang and Microsoft Corporation, https://education.minecraft.net/en-us

[4]Unity3D. Initial launch 2005 by Unity Technologies, https://unity.com/

[5]Qiskit development reports https://www.ibm.com/quantum/qiskit/history

tion with Unity, where we defined specific functions and mapped a variety of player behaviors that would trigger quantum circuit simulation. The results of these simulations were then transmitted back to the game systems as structured data points, which dynamically influenced gameplay mechanics and generated variations in the player's experience. As described in the publication, there were three main elements of the game design in which Qiskit has been integrated:

- *Word map and fog of war.* The initial design aimed to have map and environment reshaping as the player progresses in the game, affected by the gameplay choices and play styles. The procedural generation of the map and its dynamic nature was an easy start for implementing Qiskit, since this approach has been done before by the IBM team [27]. It worked well, as was expected.

- *In-game character development and relationships.* This is a common feature in the genre of RPGs, and I wanted to explore if quantum simulations could be integrated with character development. We started with simple implementations based on player choices, not just the narrative choices but the way of choosing how to interact with the world. This approach was more demanding to tackle, as we did not want players to experience any malfunction of the character development progression or in-game relationships, which are key elements in role playing games. The simple solution (that we found working well enough) has been tested with the players and we did not encounter any major issues, nor did the players have any complaints about the characters' behaviors. This was the eye opening for me as a game designer and creative lead, where I saw a huge potential in using quantum technologies in interactive storytelling, but we have decided not to push boundaries further within the C.L.A.Y. project, and instead opted to explore these opportunities in other projects where we could learn better about the development requirements, restrictions and additional possible challenges especially in the case of game engine choices or other development tools that might be in used besides Unity3D.

- *Integration with the in-game puzzle mechanic under the name "Ombrascope device".* The game world is set in post-post-apocalypse where the world is still infested with machines governed by corrupted AI who represent a danger to humankind. One of the design choices we made intentionally was that there is no destructive gameplay (no fights or aggression towards any species, even malfunctioning machines) throughout the game set in a very hostile environment. Instead, the player needs to find solutions on how to communicate and sometimes even manipulate the machines (NPC antagonists in the game) to be able to progress towards the set goals. To do so, the player solves challenges by using an Ombrascope, a device that operates with glyphs that communicate with the machines and allows the player to be seen as a non-threat to them. As

> a game co-designer, this was the most exciting element in utilizing Qiskit, because we had less concerns of the outcome that the "machine" would respond to the player, because the player was given a task to communicate with a corrupted AI that glitches, in which case if some content received might at first seem questionable, it is expected behavior from a malfunctioning machine and therefore fit the game world perfectly. This was another eye-opening moment, where we could see that we can track the player gameplay style and affect the narrative progression in the intended way using Qiskit, while maintaining the player-centric design. Just as with the narrative design, we did not want to push the boundaries further and instead used these learnings in other R&D projects.

The game is not dependent on Qiskit. We have developed our own solutions as we do for all our games, and the player can decide if they want to use quantum simulations by simply selecting it on or off in the game settings. There are several reasons for this; firstly this is a commercial game and as such we cannot risk if the third party solutions would stop working at any point, which also includes more complex maintenance issues. Secondly, we wish to test the players' experiences having both classical and hybrid solutions and see how they may affect the players' choices, gameplay styles and motivations. Furthermore, it allows us to better understand how quantum simulations and direct connection to the quantum computer in the future may work, and what additional challenges we might need to consider. This approach allows us to learn better about their potential as well as disruptions in the subject of game design practices. The game is in the final stages of development, and we expect the global launch in the near future. Once the game is globally launched, we will be able to get an adequate amount of data that will enable us to truly understand the impact this experiment has made.

3.2 Quantum Mechanics From the Point of View of a Game Designer

Thus far, most quantum-based games have been done as research projects by a variety of research groups and scholars, with different objectives than what would apply to game designers, primarily within quantum physics research, outreach or other scientific purposes [7]. Unfortunately, many research-based games and gamified solutions do not tend to remain available on the market, quite often the published articles and the results of the research projects are the only traces of these games. Often the ownership of the products lays within academic institutions that do not have dedicated team to handle the upkeep of the legal and technical requirements by the distribution platforms and therefore get removed from the game stores.

According to Piispanen et al. [28], articles published on quantum games date

back to the early 1980s, highlighting key examples such as Atari's Quantum arcade game and Greg Egan's Quantum Soccer. Throughout the years, educational and citizen science games, such as Quantum Moves and Quantum Tiq-Taq-Toe, which aim to teach quantum mechanics concepts interactively, have appeared. This article also covers the development of games on quantum computers, including Cat/Box/Scissors and Quantum Battleship, which utilize quantum computing within the gameplay [28].

Gamification has had a significant role in quantum physics outreach and in the development of educational programs, providing tools to demystify quantum physics to the general public. Some of the common practices include usage of user interaction data to improve the scientific methods though citizen science projects [29]. More recently, game jams and hackathons have had an immense effect in these attempts, which also introduced game developers to the quantum technologies as possible tools to use in their own development practices [30]. I have had the privilege of contributing to two gamification projects led by Prof. Sabrina Maniscalco and her research team, in exploring the implementation of quantum numerical simulations developed by her team in VR environments. The projects are "QWiz" and "QPlayground", used in quantum physics education and outreach, and the process and results of the projects are described in detail in Publication III.

In Publication IV, my co-authors and I shared the current state of the art of quantum technologies in developing games and learnings of our individual professional experiences. Research on the intersection of game development and quantum mechanics is an increasingly active field, and the new R&D groups worldwide who work on quantum-classical hybrid systems are becoming more established peers who provide commercially viable and accessible hardware and software that the rest of us can get more literate in this field. One of such innovations is the Quokka Quantum[6] by Eigensystems, which is an emulator of a 30-qubit quantum computing system, launched in 2024.

Thus far, user experience design, as well as interface design (UX and UI designs) in quantum computation, is still in the early stages of development due to their complexity. Currently, most quantum simulations and tools are available in various programming languages, with most accessible through Python code. Ensuring that the same content is accessible to a wide range of users, including those with non-physics or limited coding experience, is highly demanding and not currently offered by any platform on the market. In addition, providing effective feedback to users about their actions within quantum simulations is also in the early stages of development and requires further assessment. Most known are IBM Q Experience and Classiq platforms that provide graphical user interfaces alongside the programming language, which are well-designed but may still seem overwhelming to many users, especially non-physicists [25]. In my opinion, game developers can assist in

[6] Quokka Quantum – 30-qubit quantum computing system by Eigensystames https://www.quokkacomputing.com/

these matters, as UI and UX designs are crucial in games to be accessible, clearly communicating to the players their tasks at hand as well as enhancing intuitive and immersive user experience.

To achieve the desired goal of mutually accessible quantum-classical hybrid systems, it is necessary to have cross-disciplinary collaboration and development goals. In sections 4 and 5 I will be discussing the current initiatives as well as predicting the next steps in this area of collaborative efforts.

3.3 The Shifting Role of a Game Designer

Throughout this thesis, I have been part of both the theoretical and practical side of designing and utilizing quantum technologies within game design and interactive storytelling practices. As a result, I have observed the limitations of the current game design best practices, in which if we consider the possible future scenarios where emerging platforms of human interaction would be based on quantum systems, the current state of the art of game design is possibly not sufficient. One can argue that quantum computing affects/challenges the role and methodologies of the game designer and possibly requires establishing new best practices in game design.

Before critics step in on my statement above, for the record: classical computation is not going to be replaced by quantum computers. Not now, possibly never according to the quantum experts [26]. The need for adjustments in the principles of game design I am referring to are only applicable *if and when* the game design requirements must take into consideration the nature of the QC, which functions completely differently from classical ones. Using the principles of quantum mechanics, quantum computers use qubits instead of bits (used by the classical computers), which can represent 0, 1, or both simultaneously based on the notion of superposition [31]. By doing so, quantum computers can process multiple possibilities at once with no extra time needed to process the information. Utilizing entanglement, qubits can be interconnected across huge distances, while classical computers are static and deterministic systems. Furthermore, quantum gates, in comparison to classical logic gates, perform probabilistically [32] which makes them ideal for solving complex problems such as optimization and cryptography. Obviously, game designers do not need to navigate these technical questions, but becoming *quantum literate* enables us to navigate the game design requirements of the projects they get to develop for such platforms. This field of game design is in an incredibly early stage of development and based on my limited experience in the case studies examined in this thesis, I have discovered several approaches that may be beneficial for further examination and research.

Based on the presented case studies, the specifications of quantum technologies can offer increased computation power and a higher number of content combinations for players to experience. In addition, the content can be directly adjustable or

created by both developer and the player, allowing game designers to explore modular game design practices. The modular game design is already familiar though the procedural narrative in game design discussed in Section 2.3, in which the approach enables dynamic storytelling with personalized content, giving players actual choices to shape the gameworld. Therefore, the role of a game designer becomes one of facilitating these choices, ensuring that consequences are meaningful and contribute to the overall interactive storytelling. This shift resembles the role of a "game master" in role-playing games, where the game evolves through active contributions from all players in collaboration with the game master. Moreover, while the modular game design practices may bring exciting opportunities for game and narrative designers, it also introduces new challenges, such as balancing player freedom with a coherent narrative, managing the complexity of dynamic systems, and ensuring an enjoyable experience for a diverse player base, among many others [25].

3.4 Designing for the Next Generation of Technology and its Users

One of the significant learnings I have gained in my research and development work for this thesis concerns my observations regarding the similarity of the development approach and the processes of developing a game for the next generation of game consoles. Just as in using quantum simulations to emulate the behavior of real quantum computers, the development of games for the next-generation consoles shares similar challenges. For example, the development kits and simulations may lack some capabilities of the final console, so developers must address such potential changes that might be required later. Some of the best practices in this matter from the games industry include designing for scalability, which means that the current generation of platforms on which the game is running is built in a way that technical and content specifications can be extended and adjusted based on the new generation of technology. This includes developing modular assets and code that can be adjusted for higher resolutions, frame rates, or additional features. One benefit of console development in comparison to quantum computing is that these platforms use widely used and known classical computing systems, for which developers have vast amounts of resources for overcoming any challenges at hand, including the support by the manufacturers. In the case of quantum computing, the massive efforts of IBM in building the community-driven and accessible Qiskit platform, along with the educational programs free of charge (such as Quantum Explorers program by IBM), are in similar manner providing support for developers, however the challenge still remains that such endeavors are still not necessarily applicable in using a real quantum computer. The use of real quantum computers in development is possible but not necessarily optimal due to the exceptionally long waiting queues and overall limited access, as there are a limited number of quantum computers available worldwide currently. On a positive note, the simulations and emulators enable us to address the key performance challenges that we can prevent, such as optimization. Even if these cannot be fully tested with the players, we can anticipate certain behaviors and prevent the most obvious defects. This can apply to both hardware and software development features, including new designs of controllers, additional accessibility features and many other opportunities for improving the users' experiences.

Similarly, emulators enabling the games to be played from old consoles and platforms provide their own set of values, especially observing the historical evolution of game design, the trends and how we have established the best practices we use today in this field. In addition, from the viewpoint of the players who played the games at the time these were published in comparison to playing them decades later or having the new generation of players trying these games for the first time. From our previous discussion in Section 1 on how games are the dialogue between the designer and a player, the contextual relevance is shifted. We also see many older games be-

ing “remastered” to adhere to new technological fit, improvements in audio-visual communication and even interaction design, which introduces us to the matter of the chronotope.

3.5 Time-Space Dynamics for Game Designers

Chronotope is another term that I will discuss from literary studies, and it refers to the intrinsic connection between time and space in a narrative. It describes how temporal and spatial dimensions are artistically expressed and intertwined when it comes to the intended and perceived meaning between the author and the readers. The origin of chronotope lies with the work of literary theorist Mikhail Bakhtin [33] in which time and space in the stories represent different intentions and expectations from the reader, as we can recognize in games. As an example, in a story a road is initiating the movement towards the goals of the quest, encounters and character development, which we can recognize in game design principles and narrative methods of the “hero’s journey” [34].

In a cultural context, the chronotope can help us determine how cultural developments, films and other artforms, trends, even architecture, convey specific times and spaces of human values, ideologies and views also with regards to matters of history and future predictions. The importance of the chronotope lies in its structural role in defining the frame of the narrative and its perception between events and contexts, which we can observe with players’ reactions to retro games [35]. We can also explore the thematic elements of human experiences across times and spaces, cultural and identity contexts and their shifts. Most importantly, we can observe its interdisciplinary insights, from literature to scientific developments, and allow experts from various fields to understand the cultural, historical and social phenomena through spatiotemporal lenses.

For game designers, the chronotope is commonly applied in the interplay of time and space within the gameplay, narrative progression and play styles of the player. It is the bonding medium for narrative design and interactive storytelling principles in structurally unifying the gameplay experience. Quite often we can recognize chronotopes in level design, where each level is created within its confined space and controlled gameplay progression (set timeline), initiating an intense focus for the player on problem-solving at hand. In open world games and similar genres, it allows designers to influence the spatial and temporal features of in-game characters, for example the quest givers, their schedules, the weather, the day-night cycles and so forth. Regarding game mechanics, we can emphasize the interaction between time and space of the gameworld, influencing/guiding players on how to navigate the game. For multiplayer/social games it allows real-time interaction within the virtual spaces and its impact on the community-driven goals. Some games, like many free

to play mobile games or World of Warcraft[7], apply real time in the gameplay, where the in-game-time progresses even when the player is not playing.

The presented aspects of the chronotope are just a few examples of the wide range of its implementations in game design and development practices, and I think that quantum technologies may offer additional opportunities to expand the use of the chronotope beyond its theoretical framework. Considering the rapid pace of technical innovations in both software and hardware, which continue to challenge and reshape traditional game design practices, the concept of the chronotope may evolve into a practical design tool for the next generation of game designers.

In the next stages of my research and development work after this thesis, I aim to explore these opportunities further, including the variables we can create with the quantum-classical hybrid modular design systems. With the results of this thesis, we are still at the ideation stage where the gathered outcome provides glimpses of the possibility to tackle multiverses of players' experiences with individualistic perceptions and play styles. More importantly, how such a design approach would shape the players' reactions, expectations and possibly new needs, and how the awareness of any presence or absence of quantum systems would affect their gameplay.

[7] World of Warcraft by Blizzard Entertainment, https://worldofwarcraft.blizzard.com/en-gb/

4 Research Methodology: Theory and Practice with “Hands On” Approach

In the discourse of game design practices, I belong to the category of designers who believe that game design is the most important aspect of the game development as no amount of polished audio-visual content or story can substitute for poor design choices. If game design is not addressed with the highest priority, it will be affecting the overall experience of the players, leading to confusion or breaking the flow of their gameplay sessions. One of the main methods in my work regardless of the discipline or the game design task at hand, is to try to get the core game design principles in place as soon as possible, and only then address the challenges it may present or potentially expect in the further stages of development. This method I personally refer to as “hands on” approach, since it might not always follow the common practices or guidelines, yet it allows me to start solving most difficult challenges first and then proceed with the remaining design tasks. Therefore, if something does not work well in design structure, it should be fixed first and only then continue working on the audio-visual representation of the game.

Using this approach in utilizing quantum technology in game development, especially in designing a commercial game for a bigger number of players than in research-based games, it helped me find the most challenging aspects in the development process rather quickly, which I have given detailed review in the sections 2, 3 and 4. As a result, I wish to share some of the practices I have included in my work that I found useful, as well as practices that I think would need more testing and iterating for us to truly understand the ways we can utilize quantum simulations and computation in game design. In this chapter I wish to give a summary of publications I-V and present the overall research and development practices.

4.1 Summary of Publications and Their Cross-Disciplinary results

In this section I wish to present a summary of the published articles for the thesis, including the initial results across disciplines based on the research that has been conducted. I will also present the direct correlation to the research questions, research methodology and highlights of cross-disciplinary partnerships in Table 1.

Table 1. Publications

Pub. No.	Publication	Research Question	Methodology	Outcome
I	Narrative Design	RQ2, RQ3	Grounded theory	This publication sets the base for the discourse of interactive storytelling and the role of narrative design in creating games.
II	The Marriage of Quantum Computing and Interactive Storytelling	RQ1, RQ2, RQ3	Case study	In this publication we demonstrate direct implementation of quantum simulation tools in commercial game project, showcasing the possible opportunities to utilize QC in game development.
III	Exploring Interactive Storytelling in Virtual Reality for Teaching Quantum Physics and Computation: A Comparative Analysis of Qwiz and Qplayground	RQ1, RQ2, RQ3	Comparitive study	The publication demonstrates opportunities and challenges in practical implementation of quantum simulations for gamification and serious games development.
IV	A Chronicle of Quantum Technologies in Game and Software Development	RQ1, RQ2, RQ3	Review study	This publication establishes the state of the art of QC integration practices from multiple case studies done by different research groups.
V	Nurturing sustainable growth in a competitive market: Case study of MiTale	RQ1	Case study	In this paper we present the practices for the teams in cross-disciplinary collaboration.

4.1.1 Publication I: Narrative Design

Publication I has an emphasis on the theoretical and historical aspects of narrative design in game development. The paper establishes the fundamental role of narrative design in creating meaningful, purposeful and emotionally engaging gameplay. As an interactive media, games are interactive storytelling tools that construct player-driven experiences by utilizing branching structures, audio-visual cues and engaging gameplay mechanics. To achieve that, interactive storytelling differs from traditional narrative in its necessity to be coherent across all general alternative narrative paths.

Player immersion is one of the most important goals of interactive storytelling, and it is achieved by allowing a player to make choices, and even decide on a gameplay style, which always must result in believable consequences [36]. This multiplicity of outcomes and possible combinations has narrative designers embrace the modular storytelling methods, where components are assembled dynamically based on the players' inputs. This presents a game narrative design as a co-creative act between a player and a designer (or a game system). If we compare the usual storytelling methods to the interactive ones, we can observe that the story is differently presented to its audience (see Fig. 2).

The comparison of narrative control to narrative freedom is what we can also observe in improvisation theatre, as well as live action role-playing games. The interactivity allows the player to have agency in the story, which provides them with the notion of *meaningful* experience.

In game narrative design, we often come across the requirements of narrative agency, which contradicts to the idea of story being authored. The player can refuse to follow the intended story, while in practice all choice-based design gives an *illusion of choice*, in which the narrative designer sets the rules of the narrative progression and what type of freedom players may have in specific gameplay experiences. This problem is called a *narrative paradox* [37] and, in this paper, presented two possible solutions:

1. An author-centric approach which puts author's control as a priority and provides coherent narrative experience

2. The character-centric approach which is emergent narrative that is built upon simulations, system-controlled characters and has no guarantee of coherent narrative experience

No matter of the narrative design approach, it is important to approach the design of the narrative specifically for *interaction*. As the narrative paradox proposes, there are two extremes which either reduce or give full control of the narrative experience to the player, and of course a hybrid model in which depending on a gameplay sequence, players may encounter one or the other approach (see Fig. 3). Ideally each narrative would lead to a new and different situation, using *branching narratives*.

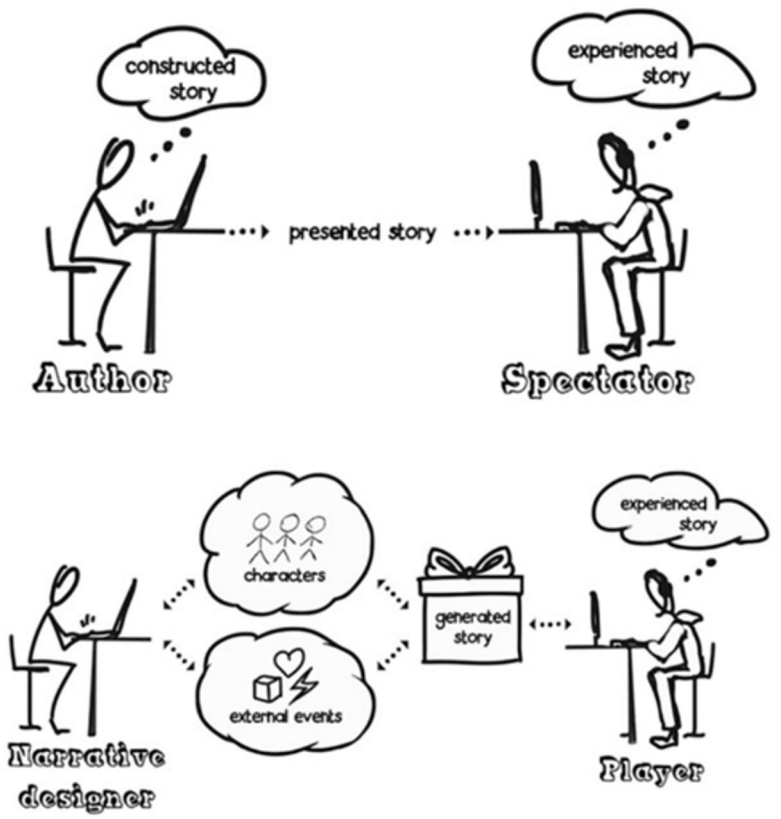


Figure 2. Traditional VS interactive storytelling structures

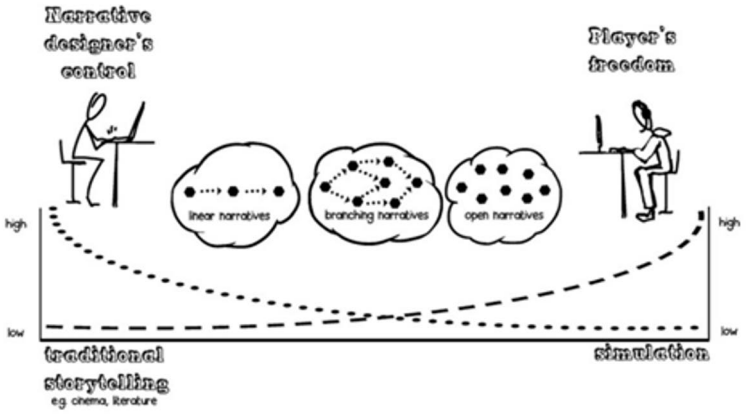


Figure 3. The spectrum of narrative types in games

Branching narratives commonly use pinch points at which the divergent paths join, reducing the number of alternatives. In this approach, the most important aspect

is the critical path, or the main set of objectives for the narrative as well as overall gameplay experience from start to finish. The critical path is an important task for a narrative designer to maintain as it guarantees that the story progresses in a coherent manner no matter of the players' choices.

The biggest challenges are in open narratives, in which no imposed sequence of narrative events is given, instead player can create own unique paths. These are commonly present in sandbox games and can include preconditions for narrative elements. Another common approach is scattering the threads of stories throughout the levels and allowing player to connect the content into larger narrative in their own pace. These threads can include missions, quests, jobs, or other type of tasks that give additional narrative content to the player.

Unlike in traditional storytelling, games provide interactive audio-visual experiences that allow narrative designer to use different storytelling tools besides pure text. In such an approach, the best practices from the disciplines of semiotics, iconography, cultural adaptation and appropriation as well as other symbol-communication methods are essential.

Each of the presented theories and practices in this publication use selected case studies to provide practical representations of these common methods for narrative design principles. As a conclusion, narrative design is where the game mechanics, visual and aural content come together to create meaningful gameplay experiences, with the aim to accommodate the players' personal preferences.

4.1.2 Publication II: The Marriage of Quantum Computing and Interactive Storytelling

In this publication, we are proposing that QC can be used to improve interactive storytelling design practices for a more immersive player experience. We present the case study of C.L.A.Y. – The Last Redemption as a commercial game that utilized Qiskit simulation by IBM for a variety of designing interaction experiences. In addition to the article's results, in this thesis I will also provide more details on the implementation process.

The article introduces the game and narrative design common practices along with the impact of game jams on initial experimentation in the field of using QC in games. The primary focus is on the case study and choices made in selecting the game design features in which the implementation of quantum technology would be the most beneficial, especially for a player-catered design approach. In Section 3.1 I have already presented the summary of the publication, including the list of game features and mechanics that were selected to implement Qiskit with, through this thesis providing more information on the implementation process itself.

The main three aspects in which Qiskit has been implemented include map exploration, puzzle mechanic with an in-game communication device and the replayability

value of the overall gameplay experience. From all three, map implementation was the simplest as it had a very clear design features when it comes to spawning areas of items and encounters, the probability of what class or nature of the item/encounter would be given to the player based on their gameplay style. More complex was the integration with the puzzle-system in which the player uses a communication device. There are set of expected outcomes as “right answers” that NPCs would recognize. We had a benefit of using symbols (see Fig. 4) as communication triggers, where different glyphs can contextually be used not just as one outcome, but possibly as both “right” and “wrong”, in which the other aspects of the players’ gameplay style and choices made previously would be important parameters in triggering the final given answer. In practice, this allowed us to have more options for the players to get the “right” answers even if they did not fully complete previous tasks, which is a rather interesting feature to have in RPG design. This type of modular design is commonly present in commercial titles with bigger financial budgets, however for the independent smaller game development teams it is not always possible to achieve. Therefore, it was quite interesting discovery that we could potentially achieve it with Qiskit simulation.

Figure 4. In-game puzzle mechanic with Ombrascope device and use of symbols

Our implementation approach relied on three main components: the use of automated game-saving data to ensure consistent and reliable progress tracking, the modular design of in-game content to allow for flexibility and scalability in gameplay development, and the careful selection of appropriate algorithms from Qiskit to address specific gameplay mechanics and computational requirements. As stated in Publication IV as well, there is still a challenge of understanding which algorithms from any available library for Qiskit or other quantum simulations are actually compatible with the specific needs of the game feature one may be designing. We focused on the algorithms that we already had previously used in other development projects.

These sets of algorithms were then tested with different behaviours and outcomes that game system would give to a player. These outcomes were primarily based on the combination of different data points listed above. The simple visualization graph (see Fig. 5) represents the structure of integration experiments made during the development, which can serve as a tool for developers to pursue own practices in implementing Qiskit with their game engine of choice, as it can be scaled to fit different software implementation environments.

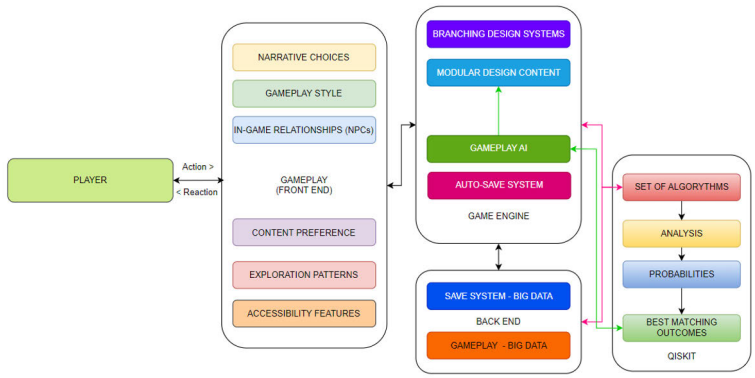


Figure 5. Simplified structure of core principles used in implementing Qiskit algorithms with game design systems

As a result, we managed to receive the variety of playthroughs that gave insights into opportunities to use QT in interactive storytelling. However, due to the limited number of players of the game demo we do not have necessary amount of data yet to confirm full potential, as the game is still in development and being prepared for the global launch on Steam platform. The research and development continue, and we are working towards sharing the results in upcoming publications.

4.1.3 Publication III: Exploring Interactive Storytelling in Virtual Reality for Teaching Quantum Physics and Computation: A Comparative Analysis of QWiz and QPlayground

Parallel to conventional interactive storytelling structures, immersive technologies such as VR enable embodied storytelling where players engage with narrative content through physical gestures and spatial navigation. In Publication III we present the use of quantum simulations in creating educational and outreach tools, targeted at students, teachers and researchers. We start with a thorough analysis of VR development practices and continue with the interactive storytelling models that were selected for the case studies. The article focuses on the comparative study of two VR projects, QWiz and QPlayground, that belong to the categories of gamification

and serious games. Both projects are developed in close collaboration between game development team at MiTale and quantum physics research teams at University of Turku and Aalto University.

Both case studies highlight the role of embodied cognition and special design in understanding complex quantum principles though intuitive and engaging interaction. QWiz places users in the role of a wizard manipulating quantum fluids via levers mapped to quantum control parameters, using real-time simulation feedback. In contrast, QPlayground transforms an interactive art installation (Quantum Garden) into a spatial, dome-like VR environment with hand-tracking for gesture-based manipulation of quantum nodes. Each of these have used different interaction models that also demonstrated the importance of UX design strategies that combine accessibility, agency and scientific simulations accuracy (see Fig. 6). While both have unique setting and narrative design frameworks, they also translate story-progression into gesture-driven puzzles and environmental storytelling, where players’ embodied interactions become both part of the narrative and a pedagogical tool.

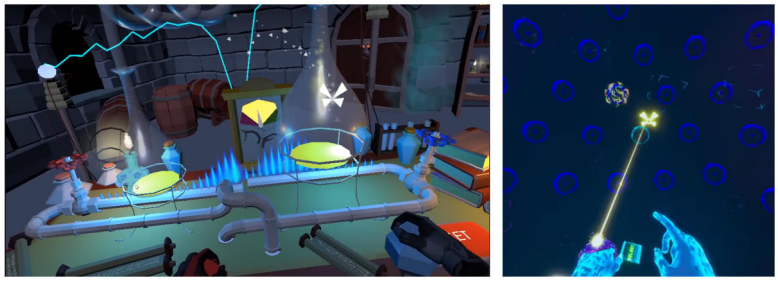


Figure 6. QWiz and QPlayground gameplay screenshots

While the results of the study gave positive outcomes in both outreach and educational activities, the team members from both disciplines (game development and quantum physics) benefited from additional insights. For the physicists, the outcome of each play was recorded and analysed further with machine learning methodologies in the study of quantum state-transfer processes within the framework of quantum optimal control. The user data was also intended to be further analysed for better understanding of the ways that players interact with the simulation, but due to iscontinuation of the governing project, such plans were not carried out. Instead, the physicists were able to learn about the challenges, limitations and advantages of numerical simulations for citizen science and outreach purposes and quantum game development. For game developers, it has been an experience in strengthening quantum literacy and use of quantum numerical simulations, which showed new potential opportunities towards using quantum computation and simulations in game design and development.

4.1.4 Publication IV: A Chronicle of Quantum Technologies in Game and Software Development

Publication IV encompasses a comprehensive review of the research and development progress made within the past decade in the field of quantum games, gamified solutions and public outreach initiatives in quantum physics education. It includes the challenges and opportunities in using quantum technologies in game-based software development for different platforms, identifies trends in quantum education and literacy, and categorizes design patterns and common challenges that facilitate analysis towards establishing best practices in development of quantum games.

Throughout this study, we have included the historical aspects of quantum games, the importance of cross-disciplinary collaboration between developers and physicists in both professional settings as well as during community-driven activities such as game jams. Providing a thorough analysis of the selected case studies including C.L.A.Y. – The Last Redemption, Pulser Studio, QWiz, and QPlayground, the article gives and overview of how QC influences game design, and its potential in game genres that can benefit complex probabilistic outcomes. Moreover, the article gives an overview of the current limitations in both QC software and hardware in achieving full integration between classical and quantum computing for commercial game production.

The article concludes that in the current stage of experiments based on the case studies presented, QC use for commercial game development is still in very early stages as challenges such as hardware constraints and algorithmic refinement persist.

4.1.5 Publication V: Nurturing sustainable growth in a competitive market: Case study of MiTale

Publication V presents a different aspect of my research work, and that is the importance of communication and sustainable strategic partnerships in fostering innovation. This article presents the challenges of the game industry market and the practices of teamwork that should be addressed, especially in a cross-disciplinary work environment. While the main topic of this study is the role of the individual in a team and nurturing creative development practices in cultivating innovation, the article also covers the challenges in communication, setting common vision and goals, as well as role of leadership in overcoming such issues.

The case study is MiTale, an independent game development company, and our team's approaches to financial independence, marketing resilience, and establishing strategic partnerships. The MiTale team has been collaborating with quantum physics and computation experts throughout the years, in both market-driven and research-based projects, which made an excellent case study to analyse cross-disciplinary research and development practices. The role of the individual, team

culture and transparency in communication (see Section 5.3) are the leading features for building well-balanced teamwork.

As the result of the study, developing a sustainable business growth in a competitive market, while fostering well-being and work balance for its team members, requires a holistic approach. By doing so, the team can implement agile practices that include fast pivoting, iteration and decision making in project development and distribution.

4.1.6 Summary: Publications Relevance in Cross-Disciplinary Collaboration Practices

Selected publications in this thesis encompass cross-disciplinary approach that deliver empirical and practical results in both theoretical and software development aspects of game design as a discipline. Moreover, the diverse methodology used for each of the publications depict the multi-layered nature of interactive storytelling practices.

The articles represent initial results in demystifying the use of QC in games, and the potential in QT being used as a dexterous tool for game designers, which was one of the main goals and impacts of this study. As a result, the thesis initiated the development of the Naviqate tool (see Section 5.2), as well as comprehensive overview of the current best practices as well as challenges in utilizing QT with game design and development. As a continuation to this thesis, in the next stages I aim to pursue research and development in QC user interfaces and interaction design, for their easier use and implementation in game and software development.

5 Results and Next Steps

Throughout my thesis, I primarily utilize experimental design based on the selected case studies which reflect the main research questions. Furthermore, the research environment was supplemented with the state of the art in quantum computing and games industry methodology, collaboration with physicists and quantum computing experts along with fellow game researchers. Most of the research environment was using online setup with virtual machines, while the player observations were done in situ. In this chapter I present the concrete results of the thesis and possible next steps of research and development in this area of study.

5.1 Does Your Game Need QC?

Before diving into the results of utilizing quantum simulations with game design, one must ask an important question: does your game need quantum technology of any sort, for what specific features and in which capacity? As discussed in Section 2, game design and development is a complex endeavour that is guided by the desired outcome in the players' experiences. Just as we carefully decide on the software and hardware specifications for our games, for example, which engine and software solutions to use as well as on which platforms our game should be playable, it should be even more important to clarify in which way quantum technology should be used and what are the direct benefits either to the development roadmap or gameplay experience(s) of the players. If there are no solid reasons for why the integration would be beneficial, you should not consider utilizing it.

Unlike quantum computing, game development has never been easier considering the vast amount of open-source and free of charge game engines and tools for individuals and teams to use in developing their games. Depending on the selected genre(s) of the game and platform(s) it should be playable on, there already exists pre-determined technical and user-experience expectations according to which the game will be taking its form. Therefore, choosing the aspect/feature of the game where quantum computing may improve that experience and expectation is the first step for a designer to decide.

In the case of C.L.A.Y. – The Last Redemption (see Section 3.1) we decided to use Qiskit simulation by IBM as it is highly accessible in comparison to other quantum simulations, and it has an active community where one can seek an ad-

vice and technical support from. By experimenting with the game design features in which we would see integration with Qiskit be the most beneficial for the players, the map-generation was the easiest first choice. The terrain generating as well as randomized spawning points for the items, encounters and other activities that players can engage with when exploring the map, was the lowest risk of testing the integration as it has been successfully done in many cases, including Minecraft terrain building [27]. When, in choosing more complex gameplay features to integrate Qiskit, we added the simulation to the puzzle mechanic and narrative content, we needed to be extra careful. Game lore allowed us to pick a puzzle mechanic that also includes the narrative structure based on the outcomes of the players' choices, which is an in-game communication device called the Ombrascope, allowing players to communicate with the NPCs: robots with corrupted AI. This made the design task way more appealing, while for the players the results of the communication with the corrupted AI machines is expected to have glitches. This allowed us to test initial boundaries of using Qiskit in both puzzle mechanic and narrative design. While more data is needed to create more robust guidelines for the developers to consider when utilizing this method, it did give initial results of being a very promising feature for procedural storytelling and branching narrative, noting however that all in-game content is created by developers and both the game system and Qiskit can modularly use it for different outcomes of gameplay. None of the in-game content is generated by any AI tool or systems as we see a high risk of providing player with possible misinformation or even gameplay deadlocks.

These initial results are the basis of starting the development of a tool called *Naviqate*, that would allow game designers to use quantum technology to find the most optimal branching systems based on the player's unique interaction with the gameworld and its encounters. In addition, the challenges of understanding which quantum algorithms are even usable by the game designer within the available libraries is another key element that brought the need for a tool such as Naviqate, as the game designer does not need to know the quantum physics behind it, instead simply understanding what its purpose is when integrating it with the game. Everything that we create and add/remove within the game design is interconnected, which means that every aspect and element has specific role and expected behaviour along with the expected results of the interactions which player may or may not perform. Therefore, adding a feature or just a technical support for the feature, in this case using quantum technology, can cause more harm to the game design than desired outcomes, which leads us back to the initial question – *why and how will this improve/enhance the gameplay experience*?

5.2 Naviqate – A Tool for More Accessible QC Integration in Game Development

I have been privileged to work with diverse teams and experts from the fields of game development, classical and quantum software development, in which we have recognized some recurring challenges for classical software developers in utilizing quantum technologies. Some of these challenges were presented in Section 3. Moreover, based on the high demand for more comprehensive tools for software and game developers to access the full potential of quantum technologies, even in the current state of development, within this thesis we initiated the development of a tool called "Naviqate"[1]. Naviqate is a software development tool with the aim to make quantum computing more accessible for classical software developers and game designers, directly serving the development processes without any prior knowledge in operating with quantum technologies. In practice, the tool aims to help software developers identify the appropriate algorithms (from open-source or custom-made libraries) that best fit their development needs based on feature specifications. Additionally, its goal is to assist in navigating the integration of these algorithms into traditional software development processes. Addressing the challenges in lack of accessibility and UI/UX design, this tool features a user-friendly interface and searchable functionalities. Ideally, we aim to include visual scripting aspects in later development. The current research project at the Department of Computing at the University of Turku, led by Dr. Jouni Smed and I, was initiated as an open-source project. The early access of the tool is scheduled for mid-2026, when we shall conduct the initial open tests with the interested parties and hope for community support in collecting initial feedback. The tool currently uses IBM's Qiskit solution, as it has the most comprehensive support and learning materials as well as an active community of users. The tool will be compatible with game development platforms such as Unity3D, Unreal Engine[2], and Godot[3]. For narrative designers, the tool is currently being integrated with Ink , an open-source narrative scripting language for games, developed by Inkle Studios[4].

The design principle of Naviqate is to act as an AI-assistant for game and software developers as well as artists and designers, facilitating easier navigation though the use of QT, especially using simulations but also in the later stages of development being used with a real QC. To assist users, Naviqate has a few main principles which

[1] Naviqate. 2023. MiTale and Department of Computing, University of Turku. AI based tool for software developers to implement quantum computation algorithms: https://www.mitalegames.com/quantumgames

[2] Unreal Engine. Initial launch 1998. Epic Games. A game development platform https://www.unrealen-gine.com/en-US

[3] Godot Engine. Initial launch 2014. Stichting Godot. A game development platform https://godotengine.org/

[4] Ink. Initial launch 2011. Inkle Studios. Scripting language tool https://www.inklestudios.com/ink/

are based on common principles of user-centered application design [38], which is to enhance the intuitive interaction with the platform and when quantum simulation principles are necessary to present to the user, it would use data visualization instead of code or math. In addition, the tool aims to have debugging tools with step-by-step breakdown of quantum operations that the user can optionally explore. In addition, if the user wishes to see more information or preview the QC tasks running, they can access it at any time. The main principles of the Naviqate tool are to assist non physicists and mathematicians in working with quantum algorithms. Acting as an AI-assistant, similar to Chat-GPT[5], it will assist in selecting the right algorithms to use in development of hybrid quantum-classical computing functions. This will be an especially beneficial tool for classical game and software developers. In this setting, the developer would ask with prompt-based search for the right set of algorithms from the available libraries, that would be the best fit based on the feature specifications under development. Once the AI-assistant provides the possible options, the list would also include the description of the compatibility with the feature under development and list possible benefits and issues in implementation. This way developers can decide which algorithm to use and prepare for the next steps in compiling, based on the presented parameters. The tool would also have a set of functions to showcase visual representation of the functions as well as code-based access to the editor for manual adjustments (see Fig. 7).

In the architectural view, the Naviqate tool serves as a "translating" tool between quantum and classical computation, which allows a software developer with no prior knowledge of quantum physics to utilize quantum computing in their development tasks regardless of the level of complexity. To compare it to some other tools on the market, I will use Adobe Photoshop[6] as an example. Photoshop is a tool for artists and creatives to use in graphic design, photo editing and digital art production. Each tool within Photoshop has specific AI-based functions for performing their tasks, e.g. brush or eraser tools. As an artist or a designer, I do not need to know how the brush works or how it was made, what I need to know is how I can use the brush tool to achieve the design task at hand. We approach the Naviqate tool in the same way – the developer does not need to know how quantum-based functions are made, they need to know how and where they can be used for the purposes of the final product under development. In the following graph, I wish to present the basic principle of Naviqate (see Fig. 7). The user interacts with the visually intuitive interface from classical computing that corresponds to the Naviqate tool, which is connected to the quantum computing systems. Based on the user's inputs/requests, the quantum system can recommend variety of algorithms to use, of which the selected best matches would be presented in more depth to the user to pick from, with detailed reason-

[5] ChatGBT AI tool by OpenAI, https://openai.com/index/chatgpt/

[6] Adobe Photoshop by Adobe, https://www.adobe.com/fi/products/photoshop/

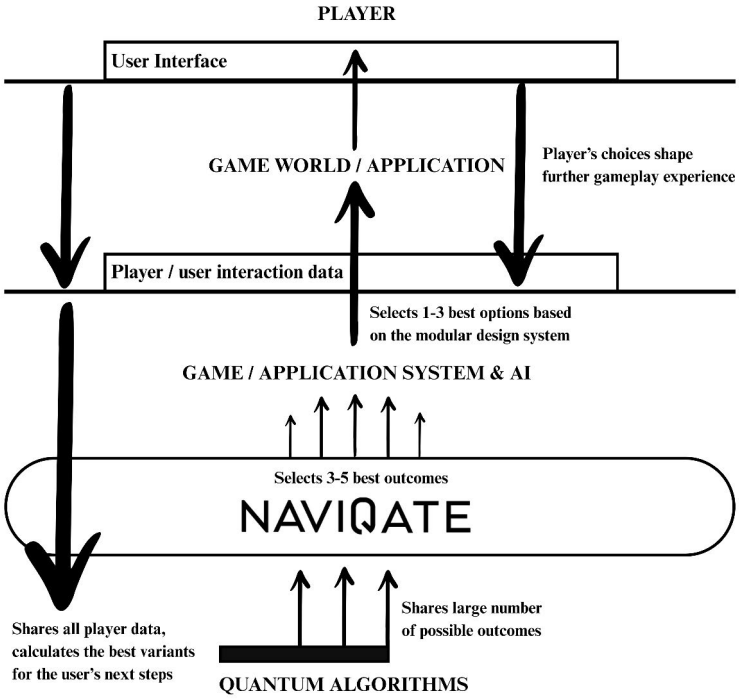


Figure 7. The structure of Naviqate tool

ing and instructions of what the pros and cons each of these are, as well as how to complete the implementation. This way the user would not be required to know more about the selected algorithms, unless they request more detailed information and possibly manually edit the quantum software side upon request. At any point the user can enter the "editor" mode, which would require knowledge of quantum software engineering. The tool is in its initial stage of development and is the subject of a further research and development project, with the aim to be tested with initial users in early 2026. On the market there are different tools that can assist in using quantum simulation and computation, however each of them requires knowledge of quantum physics; this also includes platforms such as Qiskit and Clasiq[7]. While the tool is still in the early stages of development, we can already present the user interface design concepts, along with the visualization modules and the AI-assistance (see Fig. 8). These concepts represent the design principles that would allow us to create accessible quantum programming and interaction with classical computing systems, with no prior physics or math knowledge required, nor need to know which

[7]Classiq. 2020. Classiq Platform. platform: https://www.classiq.io/

algorithms to consider using in advance. While the tool is in development, the set of features that it should include as a final product are:

- User-friendly system overview and real-time status monitoring between quantum and classical computing (e.g. live performance metrics, error monitoring)
- Execution preview before running the sequence on the QC simulation or real computer and providing scheduler, compatibility errors or any other fallback which user can prevent before sending to the queue.
- Supporting multiple coding languages, that would have standardized API and SDK support.
- Accessibility features in which access to the tool and the features presented can be set by the role of the user (e.g. designer, researcher, developer) with beginner friendly modules as well as standard software development accessibility features that include light/dark mode, adjustable UI elements and color-corrections.

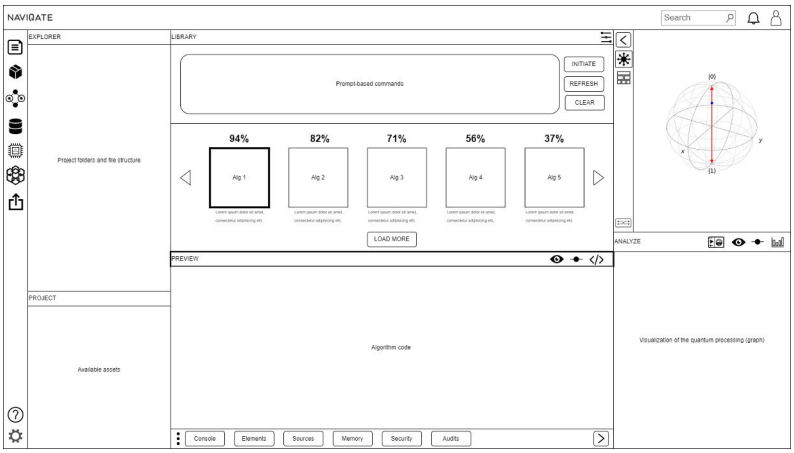


Figure 8. Naviqate UI/IX simplified view – framework concept

Through these initiatives and the development of Naviqate, I intend to continue both market-driven and research work in this field, with the aim of mitigating the described challenges. Even though we are in the very early stages of the discussed shifts, the ongoing experiments through game jams, educational games and commercially pioneering products, showcase the potential of game developers benefiting from quantum-classical hybrid systems. The upcoming developments hold increasingly promising results for solving difficult problems in AI, machine learning, and procedural content generation, which are hugely present in game development practices. As the challenges and constraints with both software and hardware of quantum

technologies persist, the journey from theory to application in utilizing quantum systems in game and software development is an exciting prospect for the evolution of interactive storytelling.

5.3 The Power of Teamwork and Community

None of the aspects of the research work presented and the results would be possible without teamwork and very close cross-disciplinary collaboration between diverse expertise throughout many years. During these years, the world did not just stand still. There have been tremendous amounts of innovations and discoveries, technical and societal pivots, which brought many solutions that can benefit the field of study I chose to pursue: using quantum computing with interactive storytelling. Teamwork, trust, and not to be afraid of things not working out is remarkably important, and it is equally important to share successes and shortcomings, the practices that did show potential and the ones where we faced challenges. To achieve any type of innovation in research and development we need to establish a safe space for challenging and questioning current practices and norms, analyze and document all aspects of the work (especially what did not go according to plans), and share with others – not being afraid of continuing the discussion and communicating with other experts and public. The benefits of such an approach are initiating the discourse on the topics and questions at hand with fresh perspectives, opinions and ideas that can lead towards resolving the challenges that we face in our work and provide qualitative and quantitative resources for the next generation of experts to lead progress further.

In my discussions with the lead supervisor of my research work at the stage where we have been selecting the list of publications to be included in the dissertation, I have decided to include Publication V, a book chapter that I wrote together with Dr. Nikolina Koporčić on the importance of the acting individual in any teamwork. In this publication, I have shared the learnings and practices in my work as a lead of a game company and how we have been developing the practices in which the empowerment and trust towards each individual equally within the team will increase the quality of the results, the productivity, and speed up the business growth that foster ethical and sustainable practices. One of the key principles to achieve innovation of any type, especially in a cross-disciplinary development as described in this dissertation, we need to have discipline-specific expertise and equally important nurture of soft skills, in particular listening and adapting [39; 40]. With extended personal experience in leading a variety of projects and teams throughout my career, listening is an essential skill for leadership – listening to the team, partners, my own intuition, the project at hand and the thoughts from the users of your product/service. Furthermore, diversity and inclusion in the workplace should not be a social imperative as it is a necessity for healthy teamwork as well as a strategic advantage that can propel the research/business/innovation towards sustained success.

Diversity and inclusion are pillars that support a thriving teamwork culture and foster innovation, where varied perspectives enhance the team's projects [41]. A diverse team with individuals from different backgrounds, ethnicities, genders, and life experiences allows a better understanding of the audiences, representation, accessibility and context of the players' expectations, enriching the quality and authenticity of the end product. Moreover, diversity enriches the creative process by introducing fresh ideas and viewpoints that might not emerge in a homogenous environment. The benefits and power of well-balanced teamwork are very often found within the communities, not just professional settings. Communities that share common interests, who have enthusiastic or even devoted individuals towards specific fields of whichever disciplines, can have an immense impact on innovation and creating the best practices. As an example, player communities as well as game development communities have a crucial role in the work presented in this dissertation. For instance, game jams have been one of the most impactful avenues for game developers to experiment with different forms of creative and technological expression, in which we have games running on a variety of platforms – from oscilloscopes to self-driving cars [42]. There are many types and forms of game jams – they can be local, regional and sometimes global events for individuals and teams to participate in creating games, usually during a set period of time. The duration of the game jam depends on the organizers, the purpose as well as the cause or topic of the jam. Most of these events are community-driven and organized by volunteers, with no competition nor prize-winning [25]. In addition, game jams are excellent initiatives for networking, exploring new skills with tools and technologies one might not be yet familiar with, and with no peer pressure or high expectations from the results.

For this thesis, the most relevant one to mention is Quantum Game Jam [43], which has been hosted in Finland and internationally since 2014 and which grew into a Global Quantum Game Jam (GQGJ) in 2020 [30]. The games made during these jams are expected to be in some way connected to quantum physics or technologies but they are not restricted in any which way or capacity. Games can be simply inspired by quantum phenomena or the use of mathematical equations to simulate certain quantum behaviors. Some games use quantum simulations such as Qiskit, and if the team has access to it, they can use a real quantum computer. The greatest impact of these events is in fostering interdisciplinary collaboration that brings together different perspectives and enhances the collective understanding of game development, interaction design and quantum concepts. These collaborative environments and community efforts help cultivate novel approaches within research and development practices in both games and quantum computing industries.

5.4 Answer to the Research Questions

To answer the research questions based on the topic of my thesis, I highlight that the results are based on the perspective of a game designer and not a quantum physicist or a software engineer. Therefore, the following answers are based on the theoretical and practical implementations of interactive storytelling, technical implementation and user-centred design practices in game development.

RQ1: What are concrete pros and cons of using quantum over classical computing in developing interactive media (e.g. games)?

Quantum computing integration is still in its early stages and currently there is not sufficient data to show direct benefits of using quantum computing in game development. While I have presented very compelling features for game designers to use to expand players' experiences, in practice it is not feasible for a gaming company to use real quantum computer integration, as the access to the QC in real time is limited and demands a steady internet connection. Technological improvements in these matters are constantly progressing, I would still highlight the importance of the QC simulators that introduce us to quantum literacy and way of shifting our perception from conventional game design practices, which can be a revolutionary step in game design as a discipline. In addition to the technical limitations, quantum AI and machine learning are also in early development and not ready for integration testing, however through hybrid quantum-classical systems we can increase the understanding of the player types, gameplay styles and preferences, as well as replayability.

RQ2: How does emerging technology such as quantum computing affect/challenge the role and methodologies of the game designer and the established best practices in game design?

In this thesis I have presented the results in utilizing quantum technologies with game design practices, as described in Section 3. As a direct answer to the research question, QC will definitely challenge the current best practices of a game designer, mainly in designing games that require the designer to give more "freedom" to the players in their playstyles, choices and content generating by players. With a vast variety of game genres, and an increasing number of cross-genres, each game will remain as a singular entity to cater to, based on its players' expectations. From my personal experiences in utilizing quantum simulations, I see a huge potential for increasing the players' engagement from an interactive storytelling point of view and shifting the role of a game designer to being more of a "game master" guiding the players in their own adventures.

RQ3: How does the user experience differ between using quantum over classical computing in interactive storytelling?

Based on primarily observations of player behaviour and acknowledging the lack of data as it requires a big number of players to provide a sufficient analysis, we can conclude following:

1. Players mainly focus on the experience and few question the design methods or technology behind it. In the majority of cases, if the game works and it is subjectively "fun", they will enjoy it and give positive feedback, which is the same type of response we see towards any commercial games.

2. Designing games using QT is similar to the approaches of developing games for the next generation of game consoles, in which use of simulators and emulators is a common practice. Besides technical challenges, we must also carefully consider the designer-player chronotope (see Section 3.5) in which theme, mechanics and setting of the game needs to attract the interest of "future players", i.e. trying to predict the commercial viability and relevance of the game at its launch from the time it takes to develop a game. Therefore, we need to address the authenticity of players' gameplay experiences in comparison to the game designers' intentions and the technological means of interaction, which can have a significant impact in players satisfaction.

5.5 The Results Summary and the Next Steps for Quantum Games

The most fruitful results of my work in this field are based on my personal role, which does not concern itself with quantum physics nor software development principles, instead I question and experiment with no fear of failure nor disappointing any aspects of these well-established disciplines. As an "outsider" I was able to approach these challenges from a novel angle, that allowed us to pursue methodologies that would not necessarily be considered in conventional game development practices. From a game designer's perspective, I have been analysing several commercial games on the market that claim to use quantum technology as the base of their game design, such as "Quantum Odyssey"[8], "QCards"[9], "Quantum Chess"[10], "Quantum

[8] Quantum Odyssey by Quarks Interactive,
https://store.steampowered.com/app/2802710/Quantum$_{O}dyssey/$

[9] QCards by QPlayLearn,
https://qplaylearn.com/game-qcards

[10] Quantum Chess by Quantum realm Games,
https://store.steampowered.com/app/453870/Quantum$_{C}hess/$

TiqTaqToe"[11] and "Hello Quantum"[12] among others. They have an incredible impact in showcasing the potential for game designers to explore their craft, but none of these games have addressed the players' needs, expectations or desires since the game design was based on the quantum physics principles and the educational or outreach goals, instead of a *game design first* approach. In my observations, "Hello Quantum" might be the most successful game when it comes to utilizing quantum physics as a *fun* element for the players, where the game itself uses a quantum principle in its core and while playing, the quantum physics do not interfere with the gameplay but let the player fully enter the gameflow and play!

The majority of quantum games tend to break the gameplay flow with some specific quantum physics feature, which then bring a higher risk of breaking the players' journey, which is what game designers always pay extra attention not to do when designing a game. As a clarification, this is not a criticism towards any of the listed games, on contrary it is an expression of admiration and acknowledgement of the variety of approaches of how one can utilize quantum technologies in game development, and for the next stages in this field of research and creating commercially viable quantum games.

Finally, the results of my research also address the challenging nature of quantum technology user experience (UX) design, as the available tools are mainly code-based and with no user interface that would make these tools more accessible for non-physicists. This results in fewer game designers and developers interested in interacting with quantum-based tools as it requires gaining an additional skillset before even beginning to explore the opportunities of implementation. To mitigate this challenge, another important feature of the Naviqate tool is to have a user-friendly interface that would allow easier onboarding to the quantum computing systems and integration for game design and development purposes.

In the later stages of my research, I have had privilege to get acquainted with new hardware and software solutions on the market that will definitely improve these efforts forward, such as the Quokka Computer by Eigensystems, quantum software solutions by Moth Quantum[13] that have creative and cultural development principles as the base of their vision and mission, as well as increasing number of qubits available in quantum computers around the world, including the new 50-qubit computer[14] made in Finland by VTT and IQM.

In one of the most recent developments of spring 2025, Moth Quantum has pub-

[11] Quantum Tiq Taq Toe by Evert van Nieuwenburg, https://everthemore.itch.io/tiqtaqtoe

[12] Hello Quantum by IBM, https://hello-quantum.en.aptoide.com/app

[13] Moth Quantum, https://mothquantum.com/

[14] VTT and IQM launch 50-qubit quantum computer, March 2025: https://www.vttresearch.com/en/news-and-ideas/vtt-and-iqm-launch-first-50-qubit-quantum-computer-developed-europe

lished a mobile game called “Space Moths”[15]. This game was presented to the public at Gamescom 2025 in Cologne Germany and runs real-time on an actual quantum computer, using either VTT, IQM or IBM QC, depending on the availability of each device at the given time. In principle, the game is built using the Roblox[16] platform and uses level generation functions based on an algorithm that is trained on the play-sessions by real players and defines what is the “fun” element from these sessions. Based on the data analysis, the algorithm generates new levels as players play, using modular elements provided by the designer. In addition to the level generation, the game also uses QC for audio design, in which music is composed with the same principles [44]. These and many more ongoing developments and technical achievements will allow us to continue providing better understanding of the current and the next generation of design challenges, as well as the opportunities that quantum computing has to offer game designers of the future.

[15] Space Moths game by Moth Quantum: https://mothquantum.com/gamescom

[16] Roblox Gaming Platform: https://www.roblox.com/

6 Conclusion

As a result of this thesis, my specialization holds both theoretical and applied research aspects, providing research and development practices (and tools in development) for aspiring interaction designers. From the perspective of a game designer, our main role is to combine creative, technical, and interpersonal skills, including communication, emotional intelligence, and teamwork. We are tasked to convey the project's vision and goals while addressing questions and concerns from the team and expectations of the players. Based on my experiences in using quantum technologies, within a carefully selected and limited scope, I recognize that traditional game design practices may fall short in a new era of experience design requirements. Quantum technologies offer increased computational power and a higher number of content combinations, enabling modular game design practices. This approach can provide even more dynamic storytelling methods with personalized content, allowing players to make choices that impact the game world in real time. The game designer's role will evolve to support these choices, ensuring that the outcomes are meaningful and enhance the overall interactive storytelling experience(s). While modular game design presents exciting opportunities, it also brings a number of new challenges such as maintaining a coherent narrative endorsing players' freedom, managing the complexity of dynamic systems, and providing an enjoyable experience for a diverse audience.

The integration of quantum computing in game development represents a revolutionary step, and as it holds promising advancements presented in these showcases of early experiments, it is crucial that the gaming industry starts to get more literate about quantum technologies and vice versa. This will enable more prominent results and an easier shift from theory to application in quantum-classical hybrid game development. In this thesis, I have provided solid ground for future research to build upon and provided potential directions that we find promising and fruitful in the not-so-distant future, especially with the new tools and solutions becoming available on the market by companies and research groups alike.

As a visual storyteller, a game developer, and experience designer – I believe that these steps will provide a new view to interactive storytelling design practices and a better understanding of the current and next generation of design challenges, as well as the opportunities that quantum computing has to offer to the designers of interactive mediums and game design as a discipline.

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