Theme Article: Special Issue on Quantum Visual Computing

A Chronicle of Quantum Technologies in Game and Software Development

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Abstract—The ongoing second quantum revolution, marked by advancements harnessing quantum phenomena, has permeated various fields, including communications, computation, and networking, collectively known as quantum technologies (QT). Quantum computing, a focal point within QT, has led to the emergence of quantum games, a novel research and development area exploring creative applications of quantum computing in game development. While more than 300 quantum games have been developed by enthusiasts and commercial parties, a comprehensive research program or state-of-the-art review is notably absent. This paper addresses this gap by conducting a thorough literature review, presenting current advancements and examples in quantum games and interactive designs, and exploring future prospects for quantum technologies in game development practices.

The anticipation of the second quantum revolution, characterized by the development of new technologies leveraging the control and manipulation of quantum phenomena, is impacting numerous fields of technology and science. These efforts span communications, computation, networking, sensing, simulation, and metrology, collectively referred to as quantum technologies (QT). There are more than 30 national and regional initiatives around the globe committing over a total of $38b public spending to the combined QT efforts by 2030s and more than 400 QT start-ups founded, mostly in the last decade [1]. Such levels of investment, and the growing interest in QT due to strategic reasons, QT being categorized under critical technologies by both the EU[1] and the US[2] causing it to be subjected under tighter export controls and investment screening regulations, and with organizations such as the European Commission and NATO coming up with their quantum strategies[3], there is a considerable interest towards the field. Within the more general ecosystem of QT, quantum computing as a research field and the development of quantum computers by private companies as commercial products received distinctive attention by several industries, resulting in formation of industrial consortia in several EU

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[1]M. Riedel et al., "Europe's Quantum Flagship initiative," 2, Quantum Sci. Technol. 4(2), 020501, IOP Publishing (2019) [doi:10.1088/2058-9565/ab042d].

[2]M. G. Raymer and C. Monroe, "The US National Quantum Initiative," 2, Quantum Sci. Technol. 4(2), 020504, IOP Publishing (2019) [doi:10.1088/2058-9565/ab0441].l. 4(2), 020501, IOP Publishing (2019) [doi:10.1088/2058-9565/ab042d].

[3]NATO's Quantum Technologies Strategy: https://www.nato.int/cps/en/natohq/official_texts_221777.htm

countries, the US, India, Japan, and others. All these led to a rapid expansion of stakeholders within the QT ecosystem [2].

Game and software developers have expressed a growing interest in utilizing their creative powers in the search of new ways of using quantum computing [3]. A new research and development area called quantum games (not to be confused with quantum games of extending game theory to quantum rules and strategies) is being formed in recent years. In the literature, quantum physics referencing games have been defined as *quantum games* quantum technologies; games might have perceivable aspects of quantum physics in them as visuals, narrative design, or through actions defined by game mechanics; they might serve the purposes of science research or education in quantum physics; or even connect to quantum computers and simulators [4], [5], [6]. To date, well over 300 quantum games[4] have been presented in public and the incorporation of quantum computing in game development has also started to attract many professional developers [4].

Although this new topic of quantum games and game development has been gaining attention, with several hundred quantum games being already released, no clear research program or a state-of-the-art review on the topic exists. In this paper, we aim to remedy that gap and review the existing relevant literature (Section 2), present the current state-of-the-art regarding quantum games and other interactive designs via some examples that the authors have been directly involved with (Section 3) and discuss the future prospects of quantum technologies and quantum simulations in game development processes (Section 4). We present our findings and conclusions (Section 5 and 6) as an invitation to all software developers, game developers and anyone interested in testing out the latest technological advancements in their respective projects and fields of interest.

2. Navigating the Game Development and Quantum Technology Landscape: A Synthesis of Previous Studies

The inquiry on the intersection of game development and quantum physics research is an increasingly active field [4], [7], [8]. In this section, we provide literature reviews on the subjects of the current stage of game development tools and practices (Subsection 2.1) and the literature on quantum game development and quantum games (Subsection 2.2).

2.1 Literature on Game Development Tools and Practices

The game development pipeline is a complex endeavor with a vast number of components such as narrative, mechanics, levels, difficulty, user interface, audio, AI, and many more [9]. The narrative component of game development involves creating coherent stories with interactive gameplay to create immersive experiences. The story helps players emotionally connect to the game, provides context for the players' actions, and enriches the game world with lore and character backstories [9]. The development process of the story involves character development and creating the theme and lore for players to engage more deeply with the game world. Frameworks such as the three-act structure[5] and the hero's journey help develop a coherent and engaging story [10], [11], [12].

Modern game engines support scripting dialogues, cutscenes and narrative branching systems, helping game and narrative designers to bring their vision to life. In linear narratives the player follows an already designed sequence of events without being able to modify how the narrative unfolds, and in an interactive narrative the player's decisions can lead to multiple outcomes [9]. Interactive narratives offer a more personalized experience to players. However, this approach requires careful planning to ensure that all alternative narratives are meaningful and work in coherence with gameplay mechanics. Otherwise, the alternative endings and/or cutscenes may break immersion, or gameplay may feel repetitive and less meaningful for players.

Another component of game development is level design, which usually begins with outlining the level objectives and setting the level's theme and how to utilize gameplay mechanics. Sketches of the level layouts help determine the level flow, setting the groundwork for game development. Level design sets the game's pacing and balance for an enjoyable

[4]The list of quantum games - https://kiedos.art/quantum-games-list/. Accessed: [21 February 2024].

[5]Ip B, "Narrative structures in computer and video games: Part 1: Context, definitions, and initial findings," Games and Culture, vol. 6, no. 2, pp. 103–134, 2011.

experience. Having a well-balanced difficulty in games is important, as it is one factor that affects players' focus and keeps them in the flow[6]. To maintain a balanced level of difficulty, some games dynamically adapt the difficulty of the game according to the player's skill[7]. Incorporating story elements into the level design gives the gameplay more depth and context. Game mechanics, visual style, and other aspects of the game should seamlessly work with the story elements and with each other to enhance the immersion.

Methods such as procedural content generation (PCG), the creation of diverse content through algorithms rather than the manual parameter setup, can be used in level design components to enrich the gameplay [13]. "No Man's Sky" and "Minecraft" are two popular examples that showcase the potential of procedural content generation in video games, which is used to dynamically generate terrains and ecosystems with endless possibilities[8]. This method aims to ensure every playthrough is different from each other and increases the game's replayability.

Game aesthetics/game art is an important component in setting the game's atmosphere and shaping players' emotions. Game art enhances the game experience by creating an immersive game world and helping players connect with the game to create the game's visual and sensorial identity. New technologies enhance the impact of game art in the games with more realistic, aesthetically pleasing art. Real-time ray tracing is one of the methods that create highly realistic visuals, amplifying the games' environment and atmosphere. By simulating the physical behavior of light, ray tracing enables realistic effects such as reflections and shadows to make the game environment more realistic [14]. Popular game engines such as Unity3D and Unreal Engine integrate ray tracing methods into their engine so that developers can easily utilize them in their games.

The visual quality enhancements of games usually come at the cost of reduced performance. This trade-off can be crucial, especially for genres such as shooter games where reaction times are essential and affect the player's enjoyment and performance. Different ray tracing techniques have been developed to get better results in terms of performance and quality. Another promising solution for better performance is using deep learning for super-resolution, an algorithm that allows games to run at lower resolutions and upscale them to higher visual qualities. NVIDIA's Deep Learning Super Sampling (DLSS)[9] is one of the latest examples of this technology.

User interface (UI) components of games are design elements that provide information about the game state to the players. The interface design should be user-friendly and show necessary information, without any elements overwhelming the players' experience. They are usually in 2D format, on the screen separated from the game, but they can also be in 3D. Since the sense of presence is really important for immersion in Virtual Reality (VR) games, 3D interfaces are found to be more realistic and have the potential to be more effective[10].

Animations are used in games to make the objects in the game move in a specific way. These objects can be characters, environmental props, or special effects. Animations bring life to the game, making it fluid and dynamic. However, creating realistic animations, especially for human-like movements, can be challenging. To create more realistic animations, motion capture technologies are used to record detailed motions in real-time. By equipping a special suit with infrared markers, performers simulate the action that will be used in games. Cameras positioned around the performer capture the performer's motions and the surrounding volume is used to reconstruct those movements in

[6] J. Schell, The Art of Game Design: A book of lenses. CRC Press, 2008.

[7] P. D. Paraschos and D. E. Koulouriotis, "Game difficulty adaptation and experience personalization: a literature review," International Journal of Human–Computer Interaction, vol. 39, no. 1, pp. 1–22, 2023.

[8] J. Togelius, G. N. Yannakakis, K. O. Stanley, and C. Browne, "Search-based procedural content generation: A taxonomy and survey," IEEE Transactions on Computational Intelligence and AI in Games, vol. 3, no. 3, pp. 172–186, 2011., J. Togelius, N. Shaker, and M. J. Nelson, "Introduction," in Procedural Content Generation in Games: A Textbook and an Overview of Current Research (N. Shaker, J. Togelius, and M. J. Nelson, eds.), Springer, 2015.

[9] Nvidia Deep Learning Super Sampling (DLSS):https://resources.nvidia.com/en-us-game-dev-dlss/how-to-successfully?ncid=no-ncid

[10] S. Safikhani, M. Holly and J. Pirker, "Work-in-Progress—Conceptual Framework for User Interface in Virtual Reality," 2020 6th International Conference of the Immersive Learning Research Network (iLRN), San Luis Obispo, CA, USA, 2020, pp. 332-335, doi: 10.23919/iLRN47897.2020.9155207

the digital world for a more realistic representation. Procedural animation algorithms can also be used to dynamically change according to the environment or adapt to specific gameplay choices of action.

Games may have multiplayer components that enable online interactions between players. These interactions add another layer to the game mechanics by making the games generally more interesting and challenging than playing against non-playable characters (NPCs) controlled via AI[11]. Multiplayer games can have systems such as matchmaking and data synchronization. These systems are hard to implement because the risk of waiting too long for matchmaking can make players quit, or too long of a delay in network transmission can cause unfairness. Game engines provide solutions such as NetCode by Unity3D and Replication by Unreal Engine to ease the implementation process of multiplayer mechanisms for developers by providing high-level features. Games may often have multiplayer components and contain AI-controlled NPCs. These NPCs can perform complex decision-making processes using methods such as behavior trees as well as move with pathfinding algorithms such as A*. However, compared to the real players, NPCs can decrease gameplay immersion if the NPCs behave unrealistically within the game world. Machine learning can be a solution for creating believable AIs by using methods such as generative models to simulate more fitting behavior.

Input controls are another game component defining the medium the player interacts with the game. This interaction can be done through a keyboard, mouse, gamepad, touchpad, virtual reality controllers or hand-tracking interface. It is important that the controls in the game are responsive and effortless for the game experience to feel sensible. Controllers should also be customized to make the game more accessible between different control-modes. Game engines usually provide their own input system for adjusting input mapping and switching between different types of controls.

[11]Dardis, F. E., and Schmierbach, M. (2012). Effects of Multiplayer Videogame Contexts on Individuals' Recall of In-Game Advertisements. Journal of Promotion Management, 18(1), 42–59. https://doi.org/10.1080/10496491.2012.646219

2.2 Quantum Computing for Game Development

Quantum computing platforms such as those offered by IBM, Google, and Microsoft offer online access to quantum computers[12]. Through these platforms, the computational power of quantum computers is accessible to a vast range of professionals, including game developers. Specific software and game engines dedicated to quantum game development, and expansions for game engines such as Unity3D have been introduced through open access sources [4]. Quantum computing software can be used to simulate quantum systems and implement quantum algorithms, which potentially have capabilities more powerful in certain tasks than what can be achieved with classical computers.

So far not many games connect to quantum computers directly due to existing technical hurdles of quantum computer access, but many claim having used quantum simulations either in the development of a game or implement the simulations directly in the game play [4], [15]. The first game on a quantum computer was developed in 2017 and was used through a terminal interface [4], [15]. Since then, the incorporation of quantum simulations and quantum computers to game development has gained popularity through open game development events such as game jams and hackathons, particularly since the release of the quantum software development tool *Qiskit* by IBM and multiple Qiskit-themed hackathons and game jams [16], [17].

Game jams are local, regional or even global events for individuals and teams to create games during a set period of time, either experimenting or learning new tools, technologies, or creative practices, as well as engaging in interdisciplinary creation. There is usually an event-specific theme upon which participants are encouraged to use as the main topic for their games or as inspiration. For example, *Quantum Game Jams* (QGJ) are considered as such since games made during the jam are expected to be in some capacity connected to quantum physics [16], [17]. The relation to quantum physics can be purely conceptual, or it can include direct scientific

[12]IBM Quantum: https://www.ibm.com/quantum, Google Quantum AI: https://quantumai.google/, Microsoft Quantum Computing: https://www.microsoft.com/en-us/research/research-area/quantum-computing/?

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implementations, the use of quantum technologies, or simulations [4].

The origins of QGJs are in citizen science (CS) games and educational games for learning quantum physics and quantum technologies [16], [17], [6], [18]. With its initial cause in scientific and research development, the QGJ has grown into a global event, which has also been the first ever game development event with access to quantum computers and tutoring on quantum computing [16]. The participants in QGJs have become more diverse throughout the years, including visual artists, writers, and musicians who have no direct contact with quantum physics or game development prior to the event by occupation or personal interest but are simply intrigued by the opportunity to contribute with their own vision and have a joint creative experience [17].

CS games extend an invitation to the general public, encouraging active participation in scientific research projects. These games harness the collective intelligence and problem-solving skills of players to address the research question(s) at hand. By merging game design principles with scientific tasks, these innovative platforms effectively bridge the gap between research and real-world applications. CS games find particular suitability in the realm of quantum physics, where abstract concepts are often difficult to convey without mathematics or traditional representation methods and has led to the development of numerical visual simulators [3], [6], [18].

Often the connection to quantum physics in quantum games presents itself in the inspiration for the perceivable aspects in the games, but quantum mechanical phenomena, such as entanglement, superposition, and quantum tunnelling can also be used to develop novel gameplay mechanics [4]. These mechanics can give players a new perspective and affect how they perceive and play the game world. Examples include various versions of quantum chess [19], [20] and quantum go [21] that utilize the principles of quantum mechanics by building upon classical versions. In the quantum version of these games, pieces can, for instance, move in multiple positions by being in a superposition state, or they can be entangled into different pieces and be affected by measurements simultaneously. This adds unpredictability to the classical versions of the gameplay.

Storytelling aspects in a game may also be incorporated using principles of quantum mechanics to create engaging and immersive experiences. Quantum Break uses quantum physics concepts to ground its science fiction mechanics, such as time travel, with a narrative that explores its consequences[13]. It complements the gameplay with a narrative that reflects a quantum phenomenon, making the mechanics and narrative coherent.

Interactive storytelling refers to a practice in which the user/player/viewer of the medium takes active participation in shaping the experience. Unlike traditional linear storytelling, where the narrative progresses along predetermined path(s), interactive storytelling allows players to choose these paths and get a sense of consequences for their actions that directly shape their experience further. This is why games have a broad impact not just as entertainment media but as tools for cognitive skills development, learning methodologies, social interactions, and well-being. Games allow exploration of the given topic, challenge, or artistic experience in a safe digital environment that can be adjusted for specific needs of the players, especially in cross-platform accessibility. This is why interactive storytelling is playing an ever-increasing role in game design and development of immersive gaming experiences and allows testing of potential uses of other emerging technologies and design principles, such as QT [8].

The use of quantum computing procedural generation techniques offers promising potential in creating vast, complex game worlds [4]. While quantum algorithms theoretically have the potential to process an extensive amount of data in certain processes faster than classical computers, the practical use of quantum applications is still in the early development stages. Quantum computing principles can already be applied in game development to create dynamic graphical and environmental iterations through a method that uses quantum interference in creating a unique blurring effect [22].

Due to algorithmic generation methods, the randomness generated by classical computers is not truly random. The methods used to get random numbers in classical computers are often seeded by environmental factors such as mouse movements or

[13] M. Kamen, "How real physics impacted time travel game quantum break." https://www.wired.co.uk/article/quantum-break-interview-sam-lake. Ac- cessed 20 February 2024.

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computer time, to break possible repeating patterns in the output [23]. For quantum computers, generating a truly random number is possible. Processes such as measuring a qubit in superposition result in outcomes that are fundamentally unpredictable and access the inherent randomness of quantum physics. Quantum randomness can be used in-game mechanics where randomness is important to ensure that these mechanics are truly unpredictable [24].

The integration of quantum computing with game development, facilitated by platforms from IBM, Google, and Microsoft, and with access to a wide range of simulators, has enabled the creation of games that incorporate quantum physics principles. These advancements have been particularly evident in the rise of QGJs, which encourage the development of quantum-inspired games by a diverse group of participants. Such games explore novel gameplay mechanics and narratives grounded in quantum mechanics, offering players unique experiences.

3. Examples of Quantum Integration in Games

In this section, the authors elaborate on their learnings and experiences on quantum games and graphical user interfaces (GUIs) for quantum computing software and numerical simulations they have been involved with: C.L.A.Y., QWiz, and Pulser Studio. With the constantly evolving landscape of QT, we find ourselves at the nexus of research and practical application. The collaborative spirit among research groups is palpable, with diverse approaches converging under the umbrella of quantum software development. The following sections unfold against the backdrop of this dynamic synergy, as we explore the various methodologies that have surfaced through ongoing research and market-driven projects.

3.1 C.L.A.Y., QWiz, and Pulser Studio

One of the first attempts in commercial quantum game production was done in 2020-2021 by MiTale, a team of game developers from Finland, together with a research group from IBM in Zürich [4], [8]. With the game project "C.L.A.Y. - The Last Redemption" they have taken a step forward and experimented with the possibilities of integrating quantum technology into the interactive storytelling design and narrative progression of a game. This role-playing game (RPG) is set in the post-apocalypse several generations after the collapse of civilization. Such a narrative setting allowed the developers to experiment with quantum simulations in multiple aspects of game design and development, such as generating environment and visual effects, character development and in-game relationships and branching narrative and encounters. QT has been tested in the following features of the game (see Fig. 1):

- Generating environment and visual effects: Procedural generation has a leading role in environment and visual effects in the game based on quantum computing technologies by IBM's team of researchers led by Dr. James Wootton [22].

- Character development and in-game relationships: Quantum physics is implemented with in-game characters, developing personalized relationships with the player's lead character based on the type of game the player pursues. Each movement, dialogue, and action or not taking action are deeply seated with the narrative side of the game, providing unique twists and outcomes for each quest.

- Branching narrative and encounters: As a narrative-driven RPG, the choice-based narrative is an obvious place in which quantum simulation can be used. The quantum effect on the narrative progression can result in many more possible endings with the same "choice" that the player may make.

FIGURE 1. Screenshot from the game "C.L.A.Y. - The Last Redemption, the use of Qiskit in map/exploration mode

While the research work is ongoing, the initial gathered results from MiTale's team and their players indicate a vast potential for using quantum computing by game designers in interactive storytelling design practices [8].

Furthermore, storytelling is just one part of the bigger design pattern the game designer can use to craft an immersive experience. Game design comes first, in which the designer sets the challenges and core mechanics. No amount of good story or impressive audio-visuals can compensate for poor game design choices. The embedded story, visuals, and other game aspects must follow game design principles. This is why quantum computing needs to be accessible to game designers and other game industry professionals so that they can explore the full potential in which quantum technologies can be utilized in the user-centered design of games. It remains a challenge that quantum technology is overly expensive and not fully accessible, as quantum computers are a rare commodity for most of us.

Quantum computing presents its own set of challenges for game designers to tackle. These challenges compel designers to step out of their comfort zone and known best practices, venturing into the development of new ones that incorporate quantum technologies as a new asset in game development. On multiple occasions, game developers have been involved in creating citizen science games for various disciplines and research purposes, including quantum physics and computation.

Games and interactive experiences can provide an immersive three-dimensional environment that amplifies the sense of presence, empowering players to explore abstract and challenging principles on their own terms. An exemplary illustration of this approach is the virtual reality (VR) game “QWiz - Quantum is Magic”[14], (see Fig. 2) a collaborative creation by the game development company MiTale and the Turku Quantum Technology (TQT) research group at the University of Turku [3], [18]. VR technology seamlessly integrates players as active participants in the digital realm, with spatial interactions closely mirroring those of the real world. This functionality allows for the direct manipulation of surroundings, faithfully replicating immediate consequences for actions.

In QWiz, players assume the role of a “quantum wizard apprentice,” learning about quantum phenomena visualized as a liquid that adheres to the laws of quantum mechanics. The game utilizes the “Quantum Black Box”[15], a numerical simulation of a quantum control optimization problem, developed by TQT, operating in real-time in both VR and web-based versions of the game [3], [18]. By creating a visualization of quantum phenomena in VR, players can dynamically adjust parameters and observe quantum effects, intuitively understanding the challenges and improving their mastery with each attempt. Simulating quantum experiments in VR settings has shown excellent preliminary results, particularly among young children. In addition to offering a way to enter the world of quantum mechanical behavior, QWiz has served as a citizen science game, collecting data from player interactions to help address topical research questions without requiring prior physics knowledge [3], [6], [18].

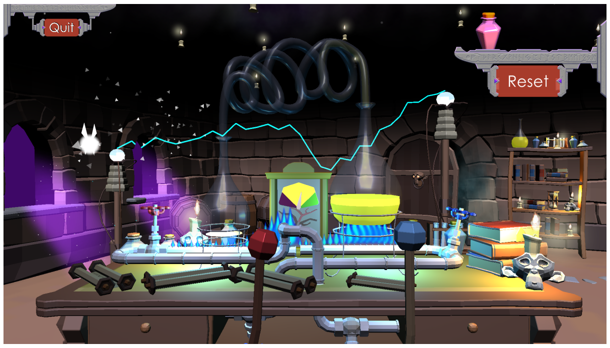

FIGURE 2. QWiz VR environment

Beyond quantum games, there are examples of graphical user interfaces (GUIs) for quantum computing software. Pulser Studio by Pasqal (pulserstudio.pasqal.cloud) is a web-based no-code platform for neutral-atoms programming, created by the Quantum Flytrap team. While it is not a game but an introductory prototyping tool for quantum computing, we note that the design obstacles are similar to those in the development of GUIs for quantum games.

One of the challenges the creators of the Pulser Studio faced was users’ lack of “quantum intuition” or established mental models when it comes to quantum computing and visualizing quantum phenomena. Mental models mean that the interface feels familiar, which eliminates the need for a lengthy introduction to how to use the tool. In the Pulser Studio, the creators tackled this by using analogies from other disciplines

[14] QWiz – Quantum is Magic, WebGL port: https://qplaylearn.it/game-qwiz

[15] Quantum Black Box - open source by Dr. Matteo Rossi; https://gitlab.utu.fi/matros/quan-tum-black-box

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and translating them into a quantum computing interface. For example, a feature for designing pulse sequences (see Fig. 3) was designed to remind common sound editing software. Typically, such software features channels with blocks of sound waves that can be horizontally rearranged and customized by the user. In Pulser Studio, users work with channels containing blocks with waveforms representing light pulses. The overall usage of the software is different, yet on the level of a specific feature, the interaction and UX are similar.

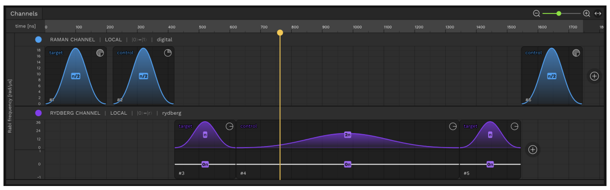

FIGURE 3. Channels feature from the Pulser Studio by Pasqal, used to design pulse sequences. Control-Z Gate example

The shared vision of these projects is to enable players to play and explore real and numerically simulated quantum phenomena, mastering skills through puzzle-based gameplay without requiring any previous experience or knowledge in quantum physics. These types of projects provide an excellent start in engaging common players with quantum technologies, creating awareness and popularizing the field of quantum games.

3.2 The Current State of Quantum Game Development

The results of quantum physics themed game developing events, for example QGJs, have been valuable for scientific communities and researchers in solving specific quantum physics problems, but they have not yet shown any significant advantages for software and game developers considering replacing classical computing solutions in games. In most cases, quantum simulations have been broadly tested by game developers as a more advanced "random event generator," which can be an exciting feature for a developer but does not make a significant difference in players' experiences [16]. Game design, in particular, is driven by a player's expectations and experiences that the designer carefully crafts through user-centered design practices. Therefore, if a feature or, in this case, quantum technology does not directly contribute to players' experiences or expectations, it does not have a value proposition that a designer would consider for use.

Another challenge for game designers and software developers is the limited use and accessibility of quantum technology (including simulations) without prior physics or advanced mathematics knowledge. Looking into the practical needs of game developers, commercial game development is a fast-paced process in which every game requires rapid iterations and testing, shaped by the chosen genre, platform, used technologies, and most importantly, feedback from the players. In such an environment, developers are looking for solutions that would ease their workload and possibly make some processes perform faster, not necessarily to start learning quantum physics and implement tools that are not comprehensive for non-physicists.

Open-source simulations, such as Qiskit by IBM, are great tools for developers to get familiar with the potential uses of quantum technologies, yet the direct use, as well as user interfaces, are in Python code and add an extra layer of accessibility challenge for game designers who do not necessarily have any coding experience. To make quantum computing more accessible for software and game developers, it is crucial to have close collaboration across these disciplines, where different professionals with diverse sets of expertise would test and develop new solutions for utilizing quantum simulations and computation specifically for its use in games.

We are still in the early stages of integrating quantum technologies with market-driven game development; however, there are significant efforts from industry professionals and scholars working on possible new solutions for easier integration. Until we have more accessible quantum software interfaces, educational efforts play an important role in building an informed society [25]. Besides game jams and hackathons, there are individual projects that serve both entertainment and education, such as "Quantum Composer" by Science at Home, "Hello Quantum" by IBM, "Quantum Game/Virtual Lab" by Quantum Flytrap and "Quantum Odyssey" by Quarks Interactive [26]. All of them are designed as commercial products that also serve the public with a scientific understanding of quantum physics.

Quantum-inspired algorithms leverage some principles of quantum computing without requiring a direct connection to the quantum computer. Running on a classical computer, these algorithms allow game

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developers to explore the opportunities of using quantum technologies in game design and production more deeply. While such games can already be fully developed as market-ready products, such as C.L.A.Y. - The Last Redemption [8], it does not necessarily mean that they would function the same when connected directly to an actual quantum computer. This means that the results of simulations can be entirely different from what they would be if the game were connected directly to the quantum computer due to additional "noise" and technical requirements (e.g., a steady connection).

There is a high level of uncertainty regarding the expected results of a game made with a simulation and intended to work directly with quantum computer integration. One practice is to have occasional connections assembled between the game and the quantum computer, even for a short period, such as several seconds, and then let the game run further on a classical computing system. This way, developers can evaluate and better estimate the game design and technical adjustments needed for the final gameplay experience utilizing quantum computing. Limited resources and access to available quantum computers challenge this approach.

4. Envisioning the Future Directions of Quantum Technologies in Game Development

In this section we present our insight into the future prospects of combining quantum technologies and quantum software into game development procedures. We see that one of the most promising and near-term achievable ways for game development to benefit from quantum technologies and quantum software is through Quantum Visual Computing (QVC).

Grover's search algorithm is one of the most well-known examples where quantum computing improves on classical computers, offering a quadratic speed up. It performs a search for an item from an unsorted list. While a classical search algorithm would require $O(N)$ steps to search through an unsorted list of N items, Grover's algorithm can achieve this in $O(\sqrt{N})$ steps. This speedup becomes important in rendering and geometry processing, where searching and optimization are the core operations [27]. The algorithm can be used in quantum rendering algorithms such as quantum ray tracing to utilize quantum mechanics concepts such as superposition and entanglement to render complex scenes[16].

An example of Grover's algorithm is Z-buffering, which is a visible-surface algorithm that checks the Z value for each pixel of all polygons in the scene. The polygon with the highest Z-value is rendered on the screen. While this is not exactly a search problem, Grover's algorithm can still be used to find the element with a minimum value in a dataset. For each pixel on the screen, a uniform quantum superposition of states can be created where each element points at a polygon in the database. The distance between the polygon and the pixel gives the Z distance [27]. From there, Grover's algorithm reduces the computational complexity from linear to quadratic, offering a more efficient rendering process for complex scenes.

Global illumination is another feature that games use to create realistic environments, and the radiosity technique can be used to compute global illumination in scenes. In radiosity, the pixel's color depends on the collection of radiosities at the corresponding point on the scene. The emitted energy summed with reflected energy for a point on the scene gives the radiosity. Techniques used for Quantum Z-Buffering and Quantum Ray Tracing can also be used for the Quantum Radiosity algorithm to reduce the complexity $O(N^2)$ of the classical task to $O(N^{3/2})$ [27]. While the theoretical framework suggests significant improvements in computational efficiency, the practical use of Quantum Radiosity is still yet to come.

In classical computers, the method for supersampling sub-pixels in rendering is generally done by Monte Carlo integration and is used in ray tracing. Introducing the quantum variant of this method is called quantum supersampling (QSS). A comparison of QSS with classical Monte Carlo integration was performed with simulation experiments and demonstrated that QSS is better at reducing mean pixel error. However, experiments made on actual quantum computers were not as successful as simulations due to the noise in the quantum computers [17].

Another method is with the algorithm for binary

[16] L. P. Santos, T. Bashford-Rogers, J. Barbosa, and P. Navrátil, "Towards quantum ray tracing," 2022

[17] E. R. Johnston, "Quantum supersampling", SIGGRAPH '16: Special Interest Group on Computer Graphics and Interactive Techniques Conference, Association for Computing MachineryNew YorkNYUnited States, 2016

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image filtering called the Quantum Coin (QCoin)[18], which, compared to QSS, works better on both simulators and actual quantum computers. QCoin is a hybrid algorithm that has both quantum and classical parts. This helps QCoin to work better in the presence of noise and offers more practical advantages than QSS[19]. Recently, the QSS algorithm was improved compared to classical and quantum ray tracing on a 3D scene rendered using Blender cycles. Results showed that the improved quantum approach created better image quality than classical ray tracing [14].

In the current state of game development, technologies such as procedural generation and rendering are already used [28]. Quantum technologies have the potential to enhance these technologies using quantum algorithms providing true randomness and other features that can inspire new gameplay mechanics. This convergence of quantum computing and gaming not only enriches the gaming landscape but also serves as an innovative platform for testing practical implementations of quantum technologies as well as educating and engaging with quantum physics concepts.

4.1 Tools for Utilising Quantum Technologies in Games

By examining the presented case studies and preliminary results from each of the projects, we can see that the integration of quantum computing and gaming technologies holds exciting potential, especially for the future directions in software development.

With the emergence of AI technologies and quantum-inspired algorithms, their use for game AI and non-player characters (NPCs) can enhance game design practices, providing additional options for dynamic decision-making processes by players and optimize complex branching systems. Real-time quantum integration can support adaptive gaming experiences based on players' interactions in both single and multiplayer settings. Quantum technology holds the potential to enhance user-generated content, modding features and community building. Hybrid quantum-classical gaming systems could seamlessly combine the strengths of both technologies, allowing a limited number of qubits to perform at their full capabilities.

However, with the current quantum solutions and resources available on the market, software and game developers face challenges in understanding which aspects of quantum computation they can utilize and, more importantly, which aspects are most beneficial for the specific features or functions under design and development. When developers embark on creating a feature or game mechanic, the chosen approach is often based on available resources and the time required to complete the task. Integrating quantum software into this process requires developers to possess a deeper understanding of the benefits it brings, both to the development process and the players' experience. Furthermore, clarity on which conditions of the quantum solution should be used and in what manner for these two aspects is not readily available within the current platforms on the market.

To make quantum computing more accessible for classical software developers and game designers, a comprehensive tool is necessary, directly serving the development processes. This tool should feature a user-friendly interface, searchable functionalities, and ideally, visual scripting aspects. A research project led by Natasha Skult and Dr. Jouni Smed from the Department of Computing at the University of Turku is currently developing the initial structure of such a tool, named "Naviqate"[20]. It aims to be available for initial testing in early 2025. The tool currently utilizes the Qiskit solution by IBM and will be applicable for game developers using Unity3D, Unreal Engine, and Godot. For narrative designers, the tool is already undergoing testing with Ink, a narrative scripting language for games developed by Inkle Studios[21].

4.2 Addressing the Limitations, User Experience Challenges and Role of a Game Designer in Quantum Game Design

Regardless of the physical systems and specifications of the quantum computers, creating highly accessible QT user experience and interaction design is

[18] C. Cantwell, "Quantum chess: developing a mathematical framework and design methodology for creating quantum games," 2019

[19] N. H. Shimada, T. Hachisuka, Quantum Coin Method for Numerical Integration, Computer Graphics Forum, May 2020

[20] Naviqate - tool under development by Natasha Skult as part of doctoral research project "Interactive Storytelling with Quantum Computing" at University of Turku, under the supervision by Prof. Jouni Smed: https://www.mitalegames.com/quantumgames

[21] Ink by Inkle Studios: https://www.inklestudios.com/ink/

crucial. Designing interactive experiences requires a multidisciplinary approach, combining creative and technical knowledge, empathy, soft skills, and an understanding of the target users. User experience design, as well as interface design (UX and UI designs), is in the early stages of development for quantum simulations and technologies due to their complexity. Currently, the majority of QT 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.

A specific challenge is providing effective feedback to users about their actions within quantum simulations. The feedback system, as well as guidance on using the tools most effectively, is still in the early stages of development. IBM Q Experience and Classiq[22] platforms provide well-designed graphical user interfaces alongside the programming language, but may still seem overwhelming to many users who are not affiliated with quantum physics. In game development, UI/UX design best practices have evolved significantly due to the necessity for cross-platform compatibility and user accessibility features. By applying inclusive UI/UX design principles from the games industry [9], quantum technology experts can benefit from their insights in solving the visual representations of the complex features these platforms provide. Furthermore, these are iterative processes that require continuous refinement based on user feedback and changing requirements. Depending on the platform, creating user interfaces for quantum technologies requires a deep understanding of the technical aspects involved, including the implementation of frameworks and tools. This ensures that responsive design with a clear visual hierarchy and prioritized readability (font sizes, line spacing, contrast, etc.) will ensure easier navigation and intuitive interaction [9].

The role of a game designer is a combination of creative, technical, and interpersonal skills, including communication, emotional intelligence, and teamwork. In traditional game design practices, designers are tasked with crafting the overall gameplay experience and addressing specific features and mechanics within the game. In larger teams, game designers may lead a dedicated group handling mechanics, level design, in-game economy, and other aspects falling under game design. In smaller indie teams, a game designer might work independently and may take on additional roles, such as Team Leader. Regardless of the team size, the game designer holds the responsibility of communicating the project's vision and goals to the team, answering questions, and addressing concerns from both the team and players.

Applying traditional game design practices might prove insufficient when working with quantum computing, and thus the role of a separate "quantum designer" has been suggested to accompany game designers and software designers [18]. The specifications of quantum technologies can offer increased computation power and a higher number of content combinations for players to experience. Moreover, the content can be directly adjustable or created by the player, allowing game designers to explore modular game design practices. This approach enables dynamic storytelling with personalized content, giving players actual choices to shape the game world [8]. One of the novel and very valuable advantages in potential use of QT in game design and development is the modular development approach which can enhance the game design choices to be adapted into the gameplay experience along with the possible interactions of the players. The designer's new role 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 roleplaying games, where the game evolves through active contributions from all players in collaboration with the game master.

While the modular game design approach brings exciting opportunities for game designers, it also introduces new challenges. Balancing player freedom with a coherent narrative, managing the complexity of dynamic systems, and ensuring an enjoyable experience for a diverse player base are among the key considerations in this revolutionary method.

5. Discussion

In this paper we have primarily focused on providing a review and projections from within the field of quantum game development to discuss the future

[22]Classiq is quantum software platform that enables the design, optimization, analysis, and execution of quantum algorithms, https://www.classiq.io/

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prospects of quantum technologies and quantum simulations in game development processes. This is a deliberate choice, one which provides both a degree of freedom for us the authors and several limitations on top of those that arise due to the nature of this topic. First, the extend of literature on (classical) game development is several orders of magnitude greater than the existing literature of quantum game development, therefore making a complete review of game development literature or even a complete coverage of all the game development components is not possible due to the context of this study and the review we provided in Subsection 2.1 should be accepted only as representative and not as an exhaustive one. Second, most common development activities of quantum games and game development efforts utilizing quantum phenomena (particularly quantum computers) occur either in online communities or in commercial enterprises, and only rarely presented in academic media such as published articles or proceedings. Several of the authors are either personally or via their networks involved with a wide range of quantum game development activities, however, it would be entirely likely that there are efforts that fall beyond what is publicly (or privately) available to us. Therefore, the content provided in this study is mostly representative and not exhaustive this time, not due to the extent of the activities but due to their sparse and non-academic nature.

Finally, our projections on how the future of quantum technologies might impact game development should be accepted as such, projections. Quantum computers and similar quantum technologies that may be relevant for game development are still in their very early stages of development. We do not know whether a future large scale quantum computer will perform on the cloud or on-premise, or whether it will perform on superconducting circuits that require excessive cooling or on ion-trap systems that require entire vacuum systems to operate. These factors directly relate to the potential capabilities (e.g. gate operation times), costs of utilizing such systems for games, and resource consumption of these future devices. Setting out a clear and well-defined research program at this point requires introduction of a series of what-if scenarios that lead to entirely different analyses on hardware levels for the same higher-level game development components and relevant methods (e.g. ray tracing and procedural content generation). Therefore, we chose to focus on the topics we have direct experience in, while also acknowledging that these future directions are mere potential uses, as the truth is, we do not know which physical systems the future quantum computers will operate on.

6. Conclusion

The integration of quantum computing in game development represents a still young field of research and development, which already shows promising unprecedented advancements in simulation, optimization, and immersive experiences. Tracing its historical roots from theoretical concepts to practical applications in this article, the literature review underscores the transformative potential of quantum computing in game development. Current practices showcase early experiments in algorithm optimization and complex simulations, while upcoming developments hold promise for solving intricate problems in AI and procedural content generation.

As the gaming industry starts to get more literate about quantum technologies and vice versa, it stands on the cusp of a new era, where the computational power of qubits opens new opportunities for innovative gameplay mechanics and user experiences. However, challenges such as hardware constraints and algorithmic refinement persist. Nevertheless, the journey from theory to application in quantum game development remains an exciting frontier that has the potential to reshape the gaming landscape fundamentally.

We are at the very early stages of this potential transformation, which may (and possibly will) follow a trajectory which is particularly difficult to ascertain at this point. In this article, we provided a solid ground for the following research to build upon and provided some speculative future directions that we find promising and fruitful in the not-so-distant future (with some tools such as "Naviqate" already under development). We believe that further research and interest towards the topic is warranted at this point, even if to just expand our classical horizons to get a glimpse of what we can learn and utilize for game development from the microcosmos.

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