Defining Quantum Games

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Abstract

In this article, we survey the existing quantum physics related games and based on them propose a definition for the concept of quantum games. We define quantum games as any type of rule-based games that use the principles or reference the theory of quantum physics or quantum phenomena through any of three proposed dimensions: the perceivable dimension of quantum physics, the dimension of quantum technologies, and the dimension of scientific purposes like citizen science or education. We also discuss the concept of quantum computer games, games on quantum computers and discuss the definitions for the concept of science games. At the same time, there are various games exploring quantum physics and quantum computing through digital, analogue, and hybrid means with diverse incentives driving their development. As interest in games as educational tools for supporting quantum literacy grows, understanding the diverse landscape of quantum games becomes increasingly important. We propose that three dimensions of quantum games identified in this article are used for designing, analysing and defining the phenomenon of quantum games.

Keywords: Quantum Games, Game Definitions, Game Studies, Science Games, Serious Games, Gaming, Game Technologies, Quantum Art

1 Introduction

Digital games have become one of the most popular and widespread pastime activities, but games and play have always accompanied us [1]. Games are played on different devices and platforms: on computers, mobile phones, special gaming hardware, and as physical pieces, such as board games and card games. Modes of games also vary between social and solitary activities, even within a single game session. The phenomenon of games is wide and a natural part of human history and also followed the advancements of technology.

Today the development of technologies based on quantum physical phenomena, *quantum technologies*, and in particular *quantum computers* is on its crest and games have already been designed on them. So far over 300 games referencing quantum physics have been created [2] and are drawing the attention of both academics and quantum technology enthusiasts in general, but so far no suitable definition to encompass the variety of quantum physics related games has emerged. Previous works have touted the term 'quantum games' or 'quantum computer games', referring to *computer games*, where "the rules are based on quantum principles and the games use concepts as superposition, entanglement and the collapse of the wave function" [3]. In this article we broaden and deepen the definition to include games that, for example, run on a quantum computer as well as games that use quantum software, but might still not fit this earlier definition. As a clarification, this paper does not discuss the quantum extension of game theory known as quantum game theory [4, 5].

The ludosphere of quantum physics related games, meaning the realm of the games and the design, players and culture around them [6], of can only be expected to grow. Therefore a vocabulary is needed to discuss the elements of these games, their use and development. In this paper we will examine the history of digital games and quantum physics related games through the motivations for developing them and take a closer look at *how* these games are referencing quantum physics. We are exploring games that are inspired by quantum physics, games that teach the theory of quantum mechanics, games that serve the study of quantum physics and games that use quantum technologies in their implementation. In order to analyse, discuss, and develop these games and to define *quantum games* we provide three aspects that we call *the dimensions of quantum games*: 1) the perceivable dimension of quantum physics, 2) the dimension of quantum technologies and 3) the dimension of scientific purposes, like education and citizen science.

2 Digital Games and Game Definitions

In the multitude of games, digital games play a critical role in our culture today. The early history of computer games dates as far back as the history of digital computers. In 1950 one of the first games on computers was presented, when *Bertie the Brain* was exhibited at the Canadian National Exhibition (see Figure 1a). Its main purpose was to demonstrate the use of vacuum tubes together with light bulbs, and it did it by playing *Tic-tac-toe*. In 1951 *Nimrod* played the game *Nim*, again using vacuum tubes and light bulbs. The purpose for developing these early games for computers was more of an educational kind, as it illustrated the then seemingly strange idea of programming principles and algorithms. In another implementation of *Tic-tac-toe* was in 1952 at Cambridge University, where the research project *OXO* studied the human-computer interaction again using vacuum tubes, but with an upgrade of cathode ray displays (see Figure 1b). The project aimed to demonstrate the capabilities of the EDSAC computer (Electronic Delay Storage Automatic Calculator) [7].

The 1950s brought about yet more games and game-related projects for computers, such as the development of AI to play *Checkers* in *The Samuel Checkers-playing Program* by Arthur Samuel, IBM Research [8]. These early games were mostly about showcasing new technologies, educating people about them, or researching the capabilities of the technology itself. Until the creation of *Tennis for Two* in 1958, games for computers were not purely made for entertainment [9].

The value of digital entertainment started to emerge in 1962 when a game was developed not only to test out MIT's new PDP-1 computer and showcase its capabilities, but also to attract the general audience. Moreover, this game was not an implementation of an existing game, but a totally new game designed for the computer itself. The game was called *Spacewar!*, a game of space battles (see Figure 1c). *Spacewar!* was the first example of a game that showcased what computers can do *for games*, which led to the evolution of digital games today.

(a) (b) (c)

Fig. 1 (a) Life magazine photo of comedian Danny Kaye standing in front of Bertie the Brain at the Canadian National Exhibition in 1950. (Bernard Hoffman 1950), (b) The game *OXO* on EDSAC programmed by Alexander Shafto Douglas in 1952 (From the *Gaming-History* website), (c) *Spacewar!* running on PDP-1 (Joi Ito 2007). Both Bertie the Brain and EDSAC demonstrated a game of *Tic-tac-toe* against artificial intelligence and were developed mainly to demonstrate the newest advantages in computer development. *Spacewar!* was a game developed specifically for PDP-1 and aimed at a new level of entertainment to be displayed.

2.1 Defining games

Defining games and play is not straightforward and definitions of games are not immutable. Since the formation of game studies as an academic discipline, there has been a lot of attention towards the definition of games and play [10]. First academic definitions for describing games can be said to have been developed in late 1930's [11], and the most referenced works from 1950's and 1960's [12, 13] have inspired the modern game scholars to take their updated accounts on the "game definition game" [14–16]. From these, some of the most influential game definitions list features, or conditions, of what constitutes a game [11, 13, 14, 17–21]. From these a synthesis has been presented in a popular game design book *Rules of Play* by Katie Salen and Eric Zimmerman: "A game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome." [22].

The so-called "classic game model", that is focused on rule-based games, takes into account the experience of the player in the definition: "A game is a rule-based system with a variable and quantifiable outcome, where different outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels emotionally attached to the outcome, and the consequences of the activity are negotiable" [15]. We note that comprehensively defining what games are is not a straightforward task and therefore games need to be defined continuously [23]. The definition for quantum games derived in this paper is therefore to be designed in a way that it would serve the multitude of game formats as widely as possible without touching the definition of games as a phenomena. In addition, we hope our definition also stands a purpose for other creations like *quantum art* in its many forms of combining aspects of quantum physics with art, without touching the definitions of art itself [24, 25].

2.2 Defining Science Games

As the discipline of game studies has matured, we have also developed more vocabulary for different types of games. There are several academic subcategories for games. These include, for example, leisure games, educational games and science games. Many if not most games labelled as *science games*, or "science-based games", are educational games on natural sciences designed especially for kids [26–30]. But digital science games offer a greater multitude of game formats and a categorisation of science games by the different goals proposed for the player has been proposed [31]. These categories are related to training, inquiry, professional simulations and epistemic games, embodied system games and research collaboration games, such as *citizen science games*.

Gamification is the act of introducing playful, game-like elements into an originally non-game context like scientific research, as an example [32]. With gamification, solving research problems that require numerous work hours at tasks like data processing has been partly outsourced to citizen volunteers by the use of *citizen science games*. In practice this means that these people are collecting, manipulating and providing valuable data to support university-level research. Games have the prospect of being used as tools for collecting data by providing an intuitive problem-solving task directly connected to the model being researched. Games have been used to harness the human skill of pattern recognition in citizen science projects focused on, for example, protein folding for finding cures for certain diseases like in *Foldit*, aligning multiple DNA sequences as in *Phylo* and other projects including *EteRNA*, and *Galaxy Zoo* with positive results [33–37].

To find a inclusive definition for science games, we follow the definition for a *science game jam* event, which is "*a game jam where the collaboration between game makers and scientists is facilitated in order to produce games contributing to scientific work,* *directly (such as helping to solve research questions) or indirectly (such as building awareness or teaching a scientific topic).*" [38]. We propose that similarly a *science game* could refer to **a game contributing to scientific work, directly (such as helping to solve research questions) or indirectly (such as building awareness, training or teaching a scientific topic).** Games with a purpose of teaching a scientific topic or training would still be included in the definition of science games as a subgenre, but this way games like citizen science games could also be included under the term *science games* in a concise way.

Science games are included within the broader context of serious games and applied games. Games titled as *serious games* have been defined as games that are in general designed for a particular purpose and are not just for entertainment [39, 40]. The academic focus has, again, been on educational games. Serious games have been described as a genre that "explicitly focuses on education" and as "tools for the development of creativity and innovation competences" [41, 42]. Yet, we want to emphasise that this category also includes games focused on social impact, solving research problems, educating the general public and training workers to perform specific tasks, to give examples [43].

While defining the phenomenon of games is a challenge on a theoretical level, it is challenging to also keep up with the multitude of play [6]. However, conceptual tools, such as definitions, will help us improve our understanding of the expanded field of games and play and offer valuable perspective in operationalising our research questions. Therefore, it is important to continue to have the discussion about defining games and especially to offer definitions for the types of games that are new and emerging.

Fig. 2 Screenshots from game *Quantum Break* (Remedy Entertainment, Press kit). *Quantum Break* is a science fiction action-adventure third-person shooter video game, where the protagonist is able to control the flow of time. In *Quantum Game* the player solves puzzles introducing the basic actions and logic of quantum optics equipment.

3 Quantum technologies

Quantum physics is a theory stemming from the need to describe the world at the very smallest of scales. Quantum physics refers to the subatomic scales of the smallest particles, atoms, electrons, protons and photons and describes fundamentally probabilistic phenomena we are not able to witness in our everyday lives [44, 45]. Still, without quantum physical phenomena we would not have lasers, transistors, superconducting materials and therefore novelties like the modern day tiny computers we have in our mobile phones and smart watches.

The development of quantum technologies, technologies that rely on quantum physical phenomena like superposition and entanglement, has made its way from the labs towards big markets by creating controllable devices that realise quantum phenomena [46, 47]. Quantum superposition is a phenomenon, where a quantum mechanical object is able to exhibit multiple states, or qualities simultaneously. Quantum entanglement describes the endogenous property of two or more quantum objects acting inherently as a single whole as their measurement values implicate strong correlations.

A lot of recent attention in this area has focused specifically on quantum computers, computers whose computing power relies on these and other quantum physical phenomena [48–52]. The basic units for a quantum computer are quantum bits, *qubits*. Qubits work in a fundamentally different way than bits as it is possible to manipulate and control their states and take advantage of properties like quantum entanglement and quantum superposition in a computational process [53]. This is the peculiarity and advantage of quantum computing.

It is possible to simulate quantum computing classically to an extent, but for quantum computing on a large number of qubits a quantum computer is needed as the required resources of classical nature grow exponentially with the number of qubits [54, 55]. Scalable and reliable quantum computers offer a considerable advantage over even the most prominent supercomputers when it comes to specific problems like optimising a route with several stops, efficient database searches or finding the correct structures of proteins [56–58]. Quantum computing has prospects particularly in finance, drug development, industrial optimisation problems, molecular biology and cryptography [59–62].

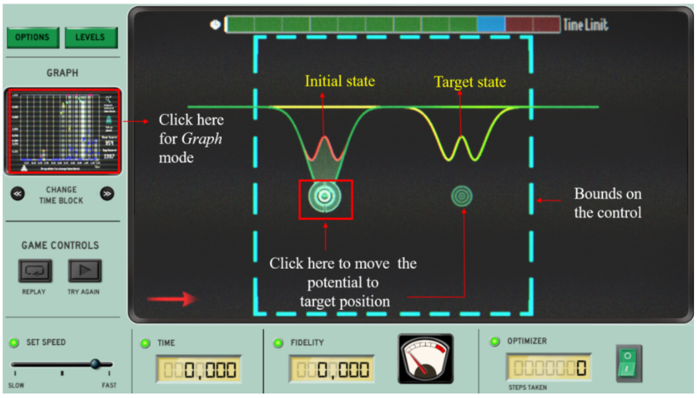
4 Quantum Physics and Games

One of the earliest if not the first commercial game bearing the word "quantum" in its title was called *Quantum* produced for Atari in 1982. In the game the player enters a subatomic world to capture particles using the optical trackball included in the arcade machine. *Game Over II*, a space adventure -shooter by Dinamic Software from 1988 had a C64 release titled *Quantum*, but the name was the only connection the game had to quantum physics. Most of the early games and other forms of entertainment, including movies and series that referenced quantum physics, have mainly been using the word 'quantum' to boost a sci-fi theme. One of the most pressing concerns is that fiction related to quantum physics can be filled with misconceptions, and may often create fantasy by replacing magic with "quantum" instead of looking deeper into the theory. A little more recent commercial game referencing quantum physics, *Quantum Break*, serves an exception, as in the development of the game the developers consulted a quantum physicist (see Figure 2) [63, 64].

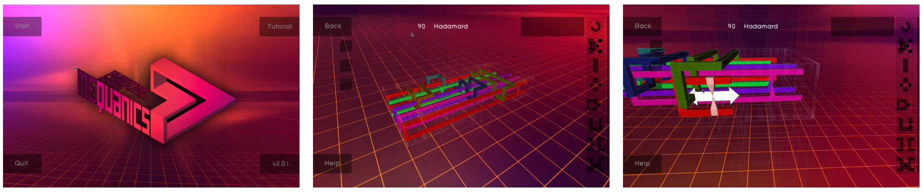
4.1 Simulating Quantum Behaviour

Notably, digital games offer greater potential for games than mere inspiration. Numerically simulated quantum principles can be incorporated into the game mechanics, and so allow people to interact with quantum phenomena rather than offer misleading fiction. Interactive tools simulating and visualising quantum physical phenomena in particular have taken advantage of this opportunity and have been used successfully to strengthen the learning and mental model building process [65–67].

This brings us to one of the most popular reasons for building games for quantum physics: education. Quantum mechanics is taught mostly in universities through books, lectures and nowadays also through e-courses, but as we have no real-life reference to quantum phenomena in our everyday lives, studying these abstract concepts often result in adversities or even misconceptions [68–74]. Games may offer captivating ways for introducing new concepts and teaching some basics on quantum mechanics, which has inspired the development of educational games and learning platforms integrating games with learning materials [30, 75–77]. Educational simulation tools have been proven to be efficient for educational purposes [65, 66, 78–82] and for research settings as shown by the Science at Home team with their study on the visualisation and simulation tool *Quantum Composer* [83].



(a)



(b)

Fig. 3 (a) An annotated interface of the *Game mode* of *Quantum Moves 2* (Shaeema Zaman Ahmed [84]), and (b) screenshots from *meQuanics*. On *Quantum Moves 2* the player controls the position of a wave-like potential confining a liquid-like quantum object and aims at moving this liquid to a pointed position. In *meQuanics* the player solves puzzles consisting of complex knotlike structures. *Quantum Moves 2* and meQuanics are citizen science games for quantum physical sciences.

Another motivation to incorporate numerical simulations of quantum physical phenomena with games lie in the use of citizen science. Quantum physics related games have been developed for data gathering and problem solving in quantum sciences. *Quantum Moves*, *Alice Challenge* and their successor *Quantum Moves 2* [85–87] are citizen science games, where players find solutions meant to optimise a certain quantum state-transfer process within the framework of quantum optimal control [46, 88–91]. In *Quantum Moves 2*, for example, the player attempts to move a 2-dimensional graph with a well-shaped confinement inside which the visualisation of a numerical quantum simulation sloshes accordingly in a water-like manner (see Figure 3a). This then responds to a procedure done with lasers in the laboratory. Other research groups have also attempted testing the fundamental theory of quantum information itself through a game called *The Big Bell Test* [92] and *meQuanics* was developed in 2016 as a prototype citizen science game for optimising quantum algorithms (see Figure 3b) [93, 94]. In the game the player aims at unravelling complex knot-like structures according to the rules given in the game (see Figure 3b). Games have also been developed to allow the public to design methods for quantum error correction, simply by figuring out how to solve puzzles like in the game *Decodoku* [95].

Turning numerical quantum simulations into interactive visual tools have also been made by, for example, the *Spin Drops* -project [96], the physical art piece *Quantum Garden* and its descendants, the virtual reality simulation *Quantum Playground* and the large-scale version of *Quantum Garden*, called *Quantum Jungle* [97–99]. The latter three also incorporate gamified elements, like a set goal and a reward. User initiates a numerical simulation of the probability distribution of a particle evolving through a network as a colourful wave through the art piece and then tries to guess where the particle ended up by touching the art piece. A colourful animation will reward the success of the observer.

4.2 Games on Quantum Computers

With games, it was possible to explore the limits of early computers. Similar motivations have been behind the development of the first *quantum computer games*, games on quantum computers. The desire to see what quantum computers are able to do and to what extent has inspired academics[100, 101]. Actors like IBM Quantum, Google AI as well as Microsoft, have developed low-level and easy to approach tutorials with playful elements and even tutorials on developing games and other programs on quantum computers [77, 102–104].

The first trials of games on quantum computers were made in 2017 on the first publicly accessible IBM Quantum device, using the newly released system development kit, *the Project Q*. Adapted to suit the strength of the qubits available then, the game *Cat/Box/Scissors*, inspired by *Rock-Paper-Scissors*, was born as the very first game running on a quantum computer [105]. This game is essentially the classic *Rock-Paper-Scissors*, but with quantum-sourced randomness at use on the opponent side. It offers the possibility of a winning tactic over the noise induced quantum sourced randomness in the opponent's moves.

A little later a multiplayer game called *Quantum Battleship* was developed also on a quantum computer. It was able to embody decoherence affecting the quantum phenomena of entanglement between two qubits, as the qubits used had a considerable amount of noise in them. Both these games were command line based games and required a long wait on processing the moves because of the long queues on the quantum computers.

Quantum Solitaire is an online card game connected to a quantum computer developed using Unity. A quantum computer is able to create certain types of data needed for the game beforehand, which therefore offered the possibility of developing a quantum computer game that would be faster and more responsive. In *Quantum Solitaire*, randomness is generated in a conventional way, but based on probabilities calculated from a prototype quantum computer. So, though the game does not access a quantum computer directly during gameplay, the play is governed by quantum phenomena. In this game the mission is to collect all the possible red and black cards from the deck using as few hands as possible. Here the player may use knowledge of quantum mechanics to draw conclusions on which combinations of flipping the cards up gives the best probabilities of success.

Educational games about quantum computers have accompanied the release of the open access cloud services. In 2018 a two-player cooperative board game *Entanglion* was created at IBM Research to introduce basic quantum computing concepts [106]. The game is available open source and introduces the players to the various aspects related to quantum computing as well as hardware and software components of a quantum computer through a narrative situated in futuristic galactic adventure [107]. The mobile game *Hello Quantum* was developed by a collaboration between IBM Quantum and the University of Basel for teaching the logic behind quantum computational operations through approachable puzzles. Educational materials, titled as *Hello Qiskit*, with gamified elements was part of IBM Quantum's interactive textbook [30, 108].

Quantum computers have not only been used as hardware for games, but their development and the advantages of quantum algorithms have also inspired level design in games. Procedural map generation procedures that combine quantum computer-generated randomness to algorithms have shown useful results [109, 110]. These proof-of-principle methods are based on the idea, where quantum interference is used to provide a unique effect on a blurring process. The idea was also generalised for the use of procedural generation in music and art in addition to computer games [111].

4.3 The Rise of Quantum Game Development

Until 2014 quantum physics related games were produced mainly by research groups mostly consisting of quantum physicists and experts. That year the first *Quantum Game Jam* was organised and led to a series of 6 quantum themed game jam events that brought together people both from the quantum physics research side and the more professional game developer side [38]. In 2019 the event combined forces with IBM Research in order to provide mentoring and a dedicated access to quantum computers. Since then other actors like the Indian community for Quantum Computing, *IndiQ*, have organised quantum computing themed game jams and hackathons [112].

Like most game jams and hackathons, also Quantum Game Jams were forced to go online like was the case in October 2021, when an online quantum game jam was organised in collaboration with Aalto University, University of Turku and IGDA Finland [113]. To date, there are at least 116 games from quantum physics themed game jams, well over 30 quantum games from hackathons and university courses like the Aalto Quantum Games course and many of them have either been developed using the quantum computing software such as Qiskit offered by IBM Quantum or even use actual quantum computers [2, 114]. Many of these game prototypes aim either at the education on quantum physics related concepts of to serve as citizen science games.

The series of quantum game jams have not only given rise to a huge number of game prototypes that relate to quantum physics, but have also provided ground for commissioned artwork like the *Quantum Garden* and the VR-installation *Quantum Playground* [97, 98, 115]. Furthermore, the development of quantum physics related games has offered means for learning about quantum physics, quantum technologies and quantum computing to the people creating these games.

5 Characterising the Dimensions of Quantum Games

Gordon & Gordon defined *quantum computer games* as *"computer games where the rules of the game are based on quantum principles, such as superposition, entanglement and the collapse of the wave function"* [3]. With this description they wanted to make the distinction of their 'quantum computer game' called the *Quantum Minesweeper* and computer games alike from *quantum game theory*, a formal mathematical theory including quantum strategies to classical game theory [3, 116, 117]. This definition was made to suit a specific educational tool and has since been cited as the definition for *quantum games*. Also more recently the term *quantum game* has been referred to as "*computer (or video) games with one or more of the phenomena from quantum physics embedded in their game mechanics*" to describe a set of quantum physics related games with educational purposes [30].

After the recent rise in the number of games that refer to or mirror quantum physical phenomena in an inspirational way and in particular after the birth of games running on quantum computers, these definitions are not enough. Quantum computers not only offer a way to design circuits to test out game theoretic quantum strategies, but have also more to offer for games. The connection of a game to quantum physics can be complex and this paper aims to bring clarity to what quantum physics related games are. Based on the examination on over 250 quantum physics related games know to the authors at the time of analysis, we propose a three-dimensional way for better defining and inspecting quantum games.

5.1 Methods

We are grounding our definition in the analysis of existing quantum physics related games and to the years of experience the authors have in developing such games. The collection of the games considered as the foundation for this analysis has been gathered since 2019 by searching through academic journals related to quantum physics, serious games on quantum physics, citizen science games on quantum physics and through events like the Quantum Game Jam [38, 113], IndiQ Quantum Game Jam and various hackathons. The list has been openly available and open for suggestions and games have been added to this list over the time of conducting this study starting from the year 2019 [2].

Prior to writing this article, the authors had among themselves used individual ways to categorise quantum physics related games catering to their personal objectives, such as, outreach and game research. In order to find a fluent way for discussing the aspects of these games also from the view of game development, the authors sought to look at the quantum physics related games known to them in order to see what attributes were the most distinctive in them. The mission was to find a comprehensive way to answer the following questions: Has a quantum computer been used in developing the game or is a quantum computer being used for playing the game? Have numerical simulations based on quantum mechanical calculus or quantum computing software (like Qiskit from IBM, Q# by Microsoft or Cirq by Google AI) been used? What has been the purpose for introducing quantum physics to the game? How is quantum physics related to what is perceivable in the game?

For the purpose of this study a number of over 250 games were studied from the *List of Quantum Games* [2]. In this list are all possible games that authors know being related to quantum physics or referencing it. The games went through an analysis consisting of the above questions. Whenever an aspect of the game was related to quantum physics but could not be described by the use of the given table of questions, a new column was added and the set of games was again viewed for possibly exhibiting the same characteristic. As an example, whenever a new perceivable aspect, like a visual simulation or the mention of a quantum physical phenomenon was noticed, it was added as a new column to the test questions as a Yes/No type field; "Is a term referencing to quantum physical phenomena mentioned in the story?" or " Are characters that are expressing simultaneous or coinciding movement or actions referred to as 'entanglement'?" As the number of these aspects grew larger, also the grouping of them was re-formed. As an example, the purposes of teaching different aspects of quantum computing or quantum theory were grouped together under "educational purposes".

Authors have taken the freedom to fill in this information for the games with no documentation, in the cases where they have been in contact with the developers, been themselves part of the development process, or otherwise acquired the information. In the beginning of the analysis the concentration was on the aspects perceivable from the game play experience, but it was acknowledged that the peripheral material related to games (such as rule books, descriptions, release notes, press kits, development event details etc.) are an essential part of the games themselves. In the cases where the word "quantum" was used merely as a loose sci-fi reference, and no other relations to quantum physics were found by the authors, these games got no markings on any of the three aspects.

By the end of the analysis, three distinctive aspects were found to constitute a quantum game. For a final testing the suitableness of these aspects, a simple Yes/No table was conducted on the list of games to answer if a game coincided with the description of a particular set of aspects. (See Table 1 as an example of a couple of games listed for testing the dimensions and A1 for more.) As no examples were found of quantum physics related games that would not have at least one of these aspects prominent, it was settled to propose these aspects as the *dimensions of quantum games*.

Table 1 List of 6 example games out of the examined 250 games characterised using the dimensions of quantum games. For each game listed a Yes/No answer was marked down in order to indicate whether the game possessed the qualities and characteristics described by the three dimensions of quantum games; The perceivable dimension of quantum physics ("Perceivable"), the dimension of quantum technologies ("Q. Tech"), and the dimension of scientific purposes ("Sci purpose"). For the latter, the different scientific purposes in the given examples are separately marked in the parenthesis. "Benchmarking" refers to benchmarking the early quantum hardware.

Game	Perceivable	Q. Tech	Scientific purpose
Quantum TiqTaqToe	Yes	No	Yes (Education)
Quantum Game	Yes	No	Yes (Education)
Cat/Box/Scissors	Yes	Yes	No
meQuanics	Yes	No	Yes (Citizen Science)
Quantum Awesomeness	Yes	Yes	Yes (Benchmarking)
Quantum Break	Yes	No	No
C.L.A.Y.	No	Yes	No

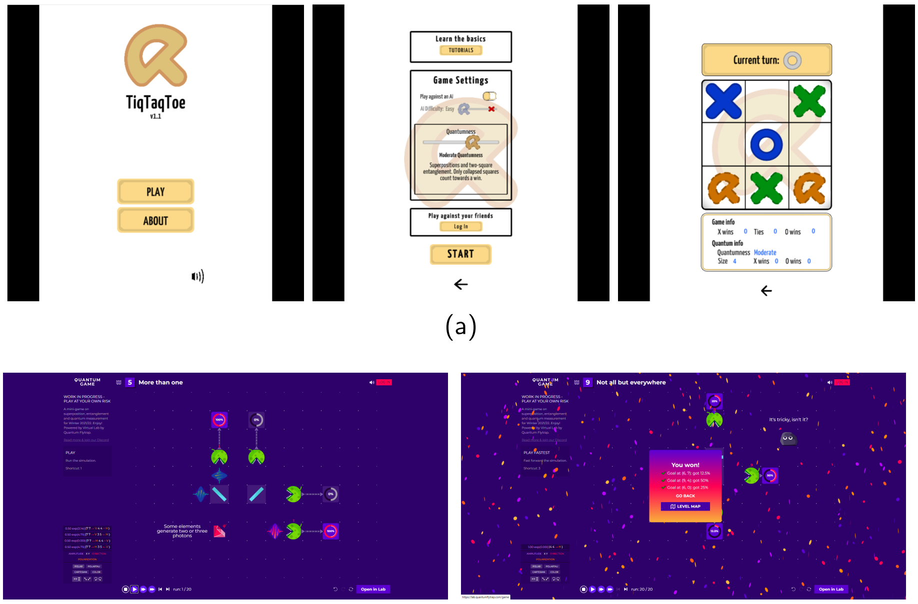
5.2 The Three Dimensions of Quantum Games

Quantum physics can be incorporated into a game by using several different methods. Therefore, any definite categories may be too strict to open up all the possible connections a game might have to quantum physics. Hence instead of providing strict categories, the concept of *dimensions of quantum games* is suggested and used by the authors. What became particularly clear and motivated the authors towards a broader definition of quantum games was that there were now games that were deeply connected to quantum physics by running on a quantum computer, though the rules of the game might not have anything to do with quantum concepts. These games do not in general fit the early definitions for either quantum games or science games.

In our study we have found that games may reference to or relate to quantum physics, quantum technologies or quantum computing through three distinctive aspects we call the *dimensions of quantum games*: the perceivable dimension of quantum physics, the dimension of quantum technologies, and the dimension of scientific purposes.

5.2.1 The Perceivable Dimension of Quantum Physics

In the **perceivable dimension of quantum physics**, "perceivable" refers to attaining awareness of quantum physics through the various layers of the game piece. This includes, for instance, the graphical, narrative, and thematic elements of the game, along with the mechanics and the rules of the game. *The reference to quantum physics in the game is perceivable by interacting with the game or with its peripheral material (such as rule books, descriptions, etc.).*



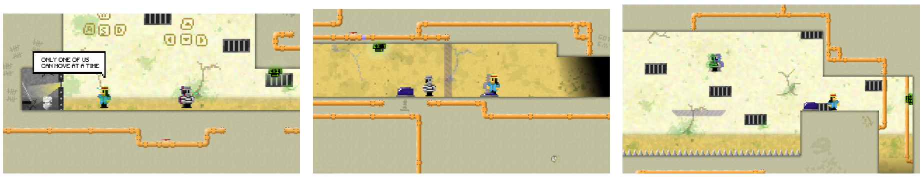
(a)

(b)

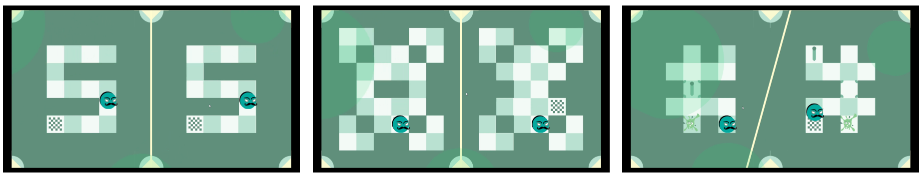
Fig. 4 Screenshots from the educational games (a) *Quantum TiqTaqToe* and (b) *Quantum Game*. In *Quantum TiqTaqToe* the basic rules of the classic Tic-Tac-Toe are enhanced with actions displaying quantum mechanical phenomena. In *Quantum Game* the player solves puzzles introducing the basic actions and logic of quantum optics equipment.

For a game to have a strong perceivable dimension of quantum physics would mean that the game depicts reference to quantum physics in multiple, noticeable ways. The game could, for instance, have a visual representation of a numerical simulation written to inherit quantum mechanical behaviour like in the games *Quantum Moves 2* or like in *Hamsterwave*, where the probability distribution of a one-dimensional Bose-Einstein condensate is portrayed as a moving wave that the player aims to reshape in order to save a hamster sailing on that wave. Also, a game could have clear rules based on quantum physical principles, like in the game *Quantum TiqTaqToe*, which combines dependencies of quantum mechanics with the classical game of *Tic-Tac-Toe* and teaches the player about the logic behind them in its tutorial (see Figure 4a). As another perceivable reference to quantum physics would be a game about a quantum physics laboratory like in the game *Quantum Game*, where the player is able to test out the behaviour of laser beams together with tools that bear resemblance to actual equipment used in a quantum optics laboratory and depicts their actions in a correct scientific manner (see Figure 4b). All the above mentioned games have a perceivable dimension of quantum physics.

Having a little less of a connection to quantum physics, but still being perceivable in a game, are the examples, where elements of the gameplay have been *inspired by* quantum physics. One such inspirational element present in some games is a character that appears to be inherently connected with another character, thereby referencing either the quantum mechanical phenomena of entanglement or quantum superposition. Games like *Quantum Entanglement* and *Quantum Labyrinth* depict this sort of characteristic (see Figure 5). The shooter game *Escape from Quantum Computer* refers to quantum physical phenomena and particles in multiple ways [118]. The narrative situates the player inside a quantum computer, where the level design inspires from the qubit alignment in the *Almanden* quantum computer by IBM. Additionally, some of the actions of the character refer to tunnelling, but have no connection to actual quantum tunnelling via a numerical simulation or by scientifically accurate means, but strive to depict the phenomenon through an allegory. Having a low or disregarded perceivable dimension of quantum physics in a game would mean that quantum physics or quantum technologies are only used thematically; merely using concepts like tunnelling or superposition for naming characters or actions in the game without a more meaningful connection to the theory of quantum physics.



(a)



(b)

Fig. 5 Screenshots from games (a) *Quantum Entanglement*, and (b) *Quantum Labyrinth*. *Quantum Entanglement* is a two-player puzzle-adventure, where the player controls two characters, and can only move one of them at a time. In *Quantum Labyrinth* the player characters are controlled simultaneously in order to solve puzzles.

The strongest example of the perceivable dimension would be a game coinciding with the definition for quantum games given by Gordon & Gordon, but slightly broadened: In a game with a strongly perceivable dimension of quantum physics *the story-line, descriptions, rules, visuals and actions in the game have clear and correct references to the theory and are based on actual quantum mechanical calculations.*

5.2.2 The Dimension of Quantum Technologies

We find it relevant to point out that the connection to quantum physics in a game does not always have to be perceivable in order to be considered as a quantum game. A game might not have a perceivable dimension of quantum physics, and yet simulate quantum physical phenomena through quantum software developed with Qiskit, Cirq, Q# or other quantum frameworks. A game without a perceivable dimension of quantum physics might even run on a quantum computer. Therefore as the second dimension we name the **dimension of quantum technologies** to captivate the *usage of quantum software or actual quantum hardware either during the gameplay itself, or during the development of the game.*

The first example of a game with a dimensionality of quantum technologies is the first ever game running on an actual quantum computer, *Cat/Box/Scissors*. The game has a thematic reference to quantum physics through a commonly used *Schrödinger's cat* reference. This game was not only designed to be played on a quantum computer, but also to invoke curiosity about the technology and methodology behind it. We want to point out that this is a feature that will likely be shared by most games implemented on quantum technologies in the coming years, before quantum computers can offer games a definite and convenient advantage. It is for this reason that it can be expected to be known to the player that a game uses quantum devices or quantum simulations, and a possible motivation for playing.

Worth discussing are games like *C.L.A.Y.* from which a demo was released by MiTale in 2021. In *C.L.A.Y.*, the dynamics of the storyline of the game will lay heavily upon emulation of interference effects on a quantum computer thereby shaping the interactive storytelling experience (see Figure 6) [119]. The design of the environment and some of the visual effects in the game are based on procedural generation sourcing on quantum computer-generated randomness, but here are no visual references to either quantum computing or quantum physics in the game itself nor is there a scientific purpose behind developing this game. Through the strong dimension of quantum technologies, this game is also to our knowledge the first ever commercial quantum computer game.

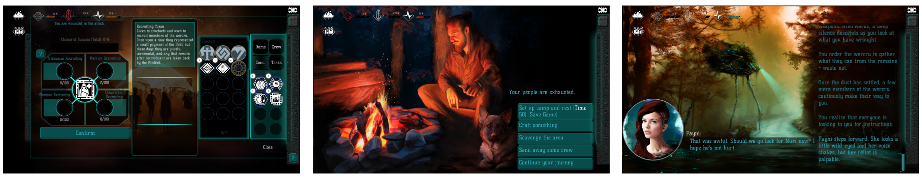


Fig. 6 Screenshots from the game *C.L.A.Y.*. In the story-driven game *C.L.A.Y.* the storyline is sourced from simulations of quantum devices.

5.2.3 The Dimension of Scientific Purposes

A game might have no visual or otherwise perceivable references to quantum physics, nor run on a quantum computer, but still have a solid connection to quantum physics through other means, such as by simulating a quantum mechanical phenomenon numerically. Examples of such games have been developed at the *Quantum Game Jam* -events, where a special tool for calculating a numerical simulation of the dynamics of a quantum mechanical particle through its time-dependent Schrödinger's equation was incorporated into games [38, 115]. Games like *Quantum Sheep*, *Quantum Cabare*, and *Quantum Fruit* use this tool, though the connection is not necessarily explained nor are there any clearly visible references to quantum physics in the games themselves.

The motivation for developing these games has been to develop prototypes of citizen science games like the kinds of *Quantum Moves 2* and *meQuanics* [94, 120]. Therefore, inspired by these we introduce a third layer characterising the **dimension of scientific purposes**. In the context of quantum physics related games, the reference to science is of course specifically the science of studying quantum physics, quantum technologies and quantum computing. Other scientific purposes include serious game motivations like education, outreach and testing the capabilities or limitations of a quantum computer like in the puzzle game *Quantum Awesomeness* [100]. An educational game like *Quantum Game* has the scientific purpose of educating the player about quantum optics in scientifically accurate ways. Therefore, *Quantum Game* fits also the dimension of scientific purposes.

Though some games might not have been successful in their original purpose as serious games, we want to include them under the definition of quantum games through this dimension. Therefore we define that *if a game is intended to be an educational game, a citizen science game, uses a tool designed for such games or otherwise has a purpose towards a scientific use, it has a dimension of scientific purposes.* One of the strongest examples of a game with quantum physics related scientific purposes is *Quantum Moves 2*, though it has not yet indisputably met its original purpose of bringing better solutions to optimisation problems compared to algorithmic methods [121, 122]. Similarly, an educational game with a focus on quantum literacy that had proven to teach the player about quantum physics would have a strong dimension of scientific purposes in addition to having a strong perceivable dimension of quantum physics.

5.3 Definition of a Quantum Game

In our findings and discussion, we have the definition of quantum games boil down to the following definition. In the context of video games, card and board games, or other games, *Quantum Games are games that reference the theory of quantum physics, quantum technologies, or quantum computing through perceivable means, connect to quantum physics through a scientific purpose or use quantum technologies.* (See Table 2)

6 Discussion

Our characterisation of quantum games using the proposed dimensions is intended to lay the groundwork for future research and the development of quantum games by providing a wider understanding of how quantum games could be part of the ludosphere of games. Future quantum game development may reveal more dimensionality and varying needs for distinction. To give an example, games with a perceivable

Table 2 The dimensions of quantum games with descriptions.

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

dimension of quantum physics could be further dissected into games with only inspirational aspects of quantum physics, games where the visuals stem from numerical simulations of quantum mechanical systems and games that include clear educational aspects, if this was of importance to a specific aim. But most importantly, we hope that our dimensions of quantum games will offer a tool for incorporating more or deeper aspects of quantum physics into quantum game development by providing clarity into the different ways a game may be a quantum game.

The three dimensions of quantum games become particularly interesting when considering the games on the outlines of these dimensions. As an example the game *Quantum Break* references quantum physics, but uses no quantum technologies in the gameplay, nor does it have any motivations to be used for educational purposes or for citizen science and does not fit the definition of a quantum game by Gordon & Gordon (see Table 1). Still the core idea of *Quantum Break* and certain visual elements of the game are deeply inspired by quantum physics and have been designed together with a quantum physicist [64]. We may conclude that *Quantum Break* is a quantum game through its carefully designed, perceivable elements of quantum physics references. Certain games like *Hopping Mode* by PiCycle from 2014 were developed at Quantum Game Jams have credited quantum physics researchers in the development process, but no other concrete reference to quantum physics is to be found related to the game [38].

It seems to be common for a quantum game to have a perceivable dimension. Still, as we have seen, there are games that have no perceivable dimension but have either the dimension of quantum technologies or the dimension of scientific purposes. Out of all the studied quantum games that had both a scientific use and in addition used quantum technologies, no example was found of a game without a perceivable dimension of quantum physics. This is likely due to the fact that quantum technologies are regarded as an interesting novel resource to use in games and are therefore also heavily underlined, whenever used. In many cases, the idea of making a quantum game is the very reason that these games were created. This causes a natural tendency to prominently feature the quantum aspect of the game. Also, both using current prototype quantum technology or designing the game to be fit for a scientific purpose introduce limitations on how the game is designed. If these limitations are noticeable to the player, it will be obvious that there is something unique about the game. By making the quantum aspect perceivable, a context is provided for the players to better understand their experience. This discussion led the authors to converse the design of such a game and play with the idea of what it would mean in practice for a game to have both a dimension of quantum technologies and scientific use, but no perceivable elements referring to quantum physics. The authors invite anyone to approach this challenge.

We note here that the presented dimensions are welcomed to be used also in defining and exploring quantum art, quantum music, quantum performing arts or other creations that reference quantum physics. We open the discussion also for other fields of sciences through the presented structure of dimensions related to the perceivable aspects, relations to scientific uses in the field and uses of possible technologies and simulations central for each field of science. We propose games related to biology, to astrophysics or cosmology, for example, could be characterised in this manner. We also invite to study the possible further layers of the dimension of scientific purposes. As for now, most serious quantum games are educational and only a few exist that have citizen science related objectives behind them [84, 115], it did not yet make sense to separate the different types of serious games like games for training or citizen science, games to create awareness, games for education and outreach under this dimension when considering quantum games. Still, we suspect that the future of quantum games might require a revisit on this dimension. We propose that acknowledging these further layers would rationalise and organise the design objectives and the development of serious games.

As discussed in section 2, the development of games on early computers was mainly motivated by outreach purposes. We have witnessed similar early steps behind the development of quantum computer games as they have evolved from known, existing games on quantum computers to the first prototypes designed for quantum computers motivated by entertainment. Digital games have evolved enormously from the time of *Spacewar!* and even motivated the further development of a variety of gaming hardware and even pushed further the development of computers and their components. So what is it that quantum technologies, or a quantum computer in particular, could give to games? One such direction might be the vision behind the game *C.L.A.Y.*, providing unique playing experiences through the use of quantum technologies (see Figure 6). If the interaction between the player and a quantum computer could be offered as an immediate, constant feedback loop, maybe the probabilistic nature of quantum physical phenomena could offer unique feedback on each run of a game [119]. First patent applications have been filed on methods using quantum computing for team composition modelling in Multiplayer Online Battle Arenas (MOBA) [123]. Same companies provide online gambling games. The ethics on the use of quantum computers for such purposes should be discussed openly.

A near-term lucrative use of quantum computers could be found in the study of procedural content generation (PCG). PCG is used for varying purposes in a great many games of different genres. This includes classical roguelikes and modern roguelites, but also 4X strategy games such as the *Civilization* series, and sandbox games such as *Minecraft* or *No Man's Sky*. When designing a content generator, one faces a number of tradeoffs, where qualities such as controllability, speed, and robustness of the generator are in partial conflict [124]. Content generators for large areas and complex systems are therefore typically limited in ambition and/or expressivity. For example, when generating a large open-world environment it becomes computationally infeasible to check for playability constraints that may emerge from paths being blocked, materials inaccessible etc. Therefore, the PCG designer will typically limit the range of what can be outputted by the generator so as to ensure its robustness, i.e. that it never outputs game-breaking content. In this context, it might be possible to use quantum computing to build content generators that are able to design larger and more systematic content while retaining playability constraints. This would probably require encoding the dependencies between features in the content in such a way that a quantum computer can resolve them. Many PCG problems could be posed as constraint satisfaction problems, and solved using e.g. Answer Set Programming, or evolutionary algorithms [125].

Much more is to investigate also about the possibilities with using quantum computers as the source of the randomness in PCG. Random numbers play important roles in cryptography, scientific and applied simulations, but also in creating an immersive experience in games. Algorithmic-based, computer-generated randomness is never truly random in the strict sense of the term and can eventually lead to sequences appearing in the outcome, noticeable for a keen eye. Methods, where environmental factors have been incorporated into the seed or into the steps of the random number algorithms have been able to provide more than just pseudo-randomness, but quantum computers may offer truly random numbers without extra trickery or biassed outcomes because the outcome of a measurement in quantum physics is based on a fundamentally random phenomena.

In our definition we did not separate the simulations of quantum technologies from the usage of these technologies, but rather aligned them along the same dimension. This is based on the reasoning that quantum computers are still at their early stages and running programs on them results in some amount of error and quantum software that simulates these devices calculate the same thing in the end and result in cleaner outcomes in some types of encoding. The "deeper" end of this dimension is open for debate and welcomes the use of quantum technologies in the future quantum games. We expect that one day we do not even separate games and quantum games from each other and see that games might have a possible quantum enhancement working on them much like the way graphic cards evolved to be used as additional computational resources.

For future work, a more thorough and systematic analysis of the collection of quantum games and their dimensions should be addressed, in particular for the purposes of education. Although the analysis of the selected games was deemed adequate for the purpose of forming a suitable definition, a closer examination of them may reveal more characteristics of the ludosphere of quantum games. There is also a lot of room for discussion when it comes to games that use well-defined numerical quantum simulations or quantum technologies for the purpose of random number generators. Do these games qualify as quantum games? We claim they do, when the usage can be identified through any of the presented dimensions of quantum games. Moreover, these specific examples underline the importance of familiarisation and education of the teams developing quantum games. In order to develop more than just a fancy random number generator, the development process requires expertise in both quantum physics and game design [115].

7 Conclusion

In this article, we have defined quantum games through their characteristics. In our model, quantum games are analysed and defined by a set of three dimensions described as the *perceivable dimension of quantum physics*, the *dimension of quantum technologies* and the *dimension of scientific purposes*. A game may exhibit one or several of these dimensions and therefore be called a *quantum game*. Our dimensions offer a way to evaluate how a game may be thought of as a quantum game, and offers directions for designing a quantum game with a profound connection to quantum physics. The number of quantum games is steadily growing as quantum computing takes steps towards a playable future, and it is anticipated that quantum games will take further forms - similar to the expansion of the general ludosphere of games.

In the paper we have also provided a clearer definition for the use of the word "science games" as *games that contribute to scientific work either directly or indirectly*, and defined quantum computer games as games playable on quantum computers.

Declarations

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- **Conflict of interest/Competing interests** Not applicable
- **Ethics approval and consent to participate**: Not applicable
- **Consent for publication**: Consent granted by all the authors.
- **Data availability**: All the games related to this research are openly listed at [2]. For viewing the table used for finding the aspects and dimensions available through the corresponding author.
- **Materials availability**: The games used for the analysis are mostly available through the reference at [2].
- **Code availability:** Not applicable

- **Author contribution**: LP: Designed the study including the methods for game analysis and the writing of this article. She gathered and characterised the games, gathered the literature review, maintained article integrity, drafted and expanded sections on digital game history and quantum computer games based on JW's work, led discussions on science games and games for serious purposes, and contributed to structure and naming of proposed dimensions. Has been responsible for the overall integrity of the article through its several iterations as the corresponding author.
  MP: Updated game analysis and carefully revised the article.
  AKK: Contributed to academic literature on game definitions and play, and participated in discussions on structure and naming of proposed dimensions.
  LJ, MP, JW, JT, AKK: Discussed game analysis and interpretation of results, and contributed to the Discussion section.

Appendix A The table of quantum dimensions of the mentioned quantum games

Table A1 A complete table of quantum games mentioned in section 5 regarding the dimensions of quantum games in order of reference. List of 16 example games out of the examined 250 games characterised using the dimensions of quantum games. For each game listed a Yes/No answer is marked down in order to indicate whether the game possessed the qualities and characteristics described by the three dimensions of quantum games; The perceivable dimension of quantum physics ("Perceivable"), the dimension of quantum technologies ("Q Tech"), and the dimension of scientific purposes ("Sci purpose"). For the latter, the purpose has been marked down separately with "Edu" standing for educational purposes, "Citizen Sci" for citizen science and "Benchm" that the game has been designed for benchmarking quantum computers.

Game	Perceivable	Q Tech	Sci purpose
Quantum Moves 2	Yes	No	Yes (Citizen Sci)
Hamsterwave	Yes	No	Yes (Citizen Sci)
Quantum TiqTaqToe	Yes	No	Yes (Edu)
Quantum Game	Yes	No	Yes (Edu)
Quantum Entanglement	Yes	No	No
Quantum Labyrinth	Yes	No	No
Escape from the Quantum Computer	Yes	No	No
Cat/Box/Scissors	Yes	Yes	No
C.L.A.Y.	No	Yes	No
Quantum Sheep	No	No	Yes (Citizen Sci)
Quantum Cabare	Yes	No	Yes (Citizen Sci)
Quantum Fruit	No	No	Yes (Citizen Sci)
meQuanics	Yes	No	Yes (Citizen Sci)
Quantum Awesomeness	Yes	Yes	Yes (Benchm)
Quantum Break	Yes	No	No
Hopping Mode	No	No	Yes (Citizen Sci)

References

[1] Rollefson, G.O.: A neolithic game board from 'ain ghazal. Bulletin of the American Schools of Oriental Research **286**, 1–5 (1992)

[2] Piispanen, L.: List of Quantum Games. https://docs.google.com/spreadsheets/d/15eL8q6HoyeJ009NAQZ5JITmXnsosmsL53MP-GwRbxxI/. Accessed: 2022-05-11

[3] Gordon, M., Gordon, G.: Quantum computer games: Quantum minesweeper. IOP Science, Phys. Educ. **45**, 372 (2010) https://doi.org/10.1088/0031-9120/45/4/008

[4] Eisert, J., Wilkens, M., Lewenstein, M.: Quantum games and quantum strategies. Phys. Rev. Lett. **83**, 3077–3080 (1999) https://doi.org/10.1103/PhysRevLett.83.3077

[5] Khan, F.S., Solmeyer, N., Balu, R., Humble, T.S.: Quantum games: a review of the history, current state, and interpretation. Quantum Inf. Process. **17**(11) (2018)

[6] Stenros, J., Kultima, A.: On the expanding ludosphere. Simulation and Gaming **49**, 338–355 (2018) https://doi.org/10.1177/1046878118779640

[7] Computer, H.: OXO Game Guide: History, Origin, and More. https://history-computer.com/oxo-game-guide/ (2021)

[8] Samuel, A.L.: Some studies in machine learning using the game of checkers. IBM Journal of Research and Development **44**(1.2), 206–226 (1959) https://doi.org/10.1147/rd.441.0206

[9] Wolf, M.J.: The Video Game Explosion: a History from PONG to Playstation and Beyond. ABC-CLIO, London, United Kingdom (2008)

[10] Aarseth, E.: Computer game studies, year one. Game Studies, the international journal of computer game research **1**(1) (2001)

[11] Huizinga, J.: Homo Ludens: Proeve Eener Bepaling van Het Spel-element der Cultuur [Homo Ludens: A Study of the Play-element in Culture]. Tjeenk Willink, Haarlem, Netherlands (1938)

[12] Wittgenstein, L.: Philosophical Investigations. Blackwell Publishing, Oxford, United Kingdom (1953)

[13] Caillois, R.: Man, Play and Games. University of Illinois Press, Champaign, USA (1961)

[14] Suits, B.: The Grasshopper: Games, Life and Utopia. Broadview Press, Ontario,

Canada (2005)

[15] Juul, J.: Half-Real, Video Games Between Real Rules and Fictional Worlds. The MIT Press, Cambridge, Massachusetts, USA (2005)

[16] Stenros, J.: The game definition game: A review. Games and Culture **12**(6), 499–520 (2016) https://doi.org/10.1177/1555412016655679 https://doi.org/10.1177/1555412016655679

[17] Parlett, D.: Oxford History of Board Games. Oxford University Press, Oxford, UK (1999)

[18] Abt, C.C.: Serious games. American Behavioral Scientist **14**(1), 176 (1970) https://doi.org/10.1177/000276427001400113 https://doi.org/10.1177/000276427001400113

[19] Crawford, C.: The Art Of Computer Game Design. McGraw-Hill/Osborne Media, New York, USA (1984)

[20] Greg, C.: I have no words & i must design: Toward a critical vocabulary for games. In: Computer Games and Digital Cultures Conference Proceedings. Tampere University Press, Tampere, Finland (2002). http://www.digra.org/wp-content/uploads/digital-library/05164.51146.pdf

[21] Sutton-Smith, B., Avedon, E.M.: The Study of Games. J. Wiley, New York, USA (1971)

[22] Tekinbaş, K.S., Zimmerman, E.: Rules of Play - Game Design Fundamentals. The MIT Press, Cambridge, Massachusetts, USA (2003)

[23] Arjoranta, J.: How to define games and why we need to. The Computer Games Journal **8**(3-4), 109–120 (2019) https://doi.org/10.1007/s40869-019-00080-6

[24] Dickie, G.: Defining art. American Philosophical Quarterly **6**(3), 253–256 (1969)

[25] Young, J.O.: Defining art responsibly. The British Journal of Aesthetics **37**, 57 (1997) https://doi.org/10.1119/1.3546093

[26] Beier, M., Miller, L., Wang, S.: Science games and the development of scientific possible selves. Cultural studies of science education **7**, 963–978 (2012) https://doi.org/10.1007/s11422-012-9408-0

[27] Muehrer, R., Jenson, J., Friedberg, J., Husain, N.: Challenges and opportunities: Using a science-based video game in secondary school settings. Cultural Studies of Science Education **7** (2012) https://doi.org/10.1007/s11422-012-9409-z

[28] Migdał, P., collaborators: Science-based games. https://github.com/stared/science-based-games-list. Accessed: 2023-03-17

[29] Anupam, A.: Teaching scientific inquiry as a situated practice: A framework for analyzing and designing science games. Learning, Media and Technology **47**(1), 125–142 (2022) https://doi.org/10.1080/17439884.2021.2020285 https://doi.org/10.1080/17439884.2021.2020285

[30] Seskir, Z.C., Migdał, P., Weidner, C., Anupam, A., Case, N., Davis, N., Decaroli, C., Ercan, İ., Foti, C., Gora, P., *et al.*: Quantum games and interactive tools for quantum technologies outreach and education. Optical Engineering **61**(8), 081809–081809 (2022)

[31] Magnussen, R.: Games in science education: Discussion of the potential and pitfalls of games-based science education. Proceedings of the European Conference on Games-based Learning **1**, 339–345 (2014)

[32] Hamari, J.: Gamification. In: G. Ritzer, C. Rojek (Eds.), The Blackwell Encyclopedia of Sociology. John Wiley & Sons, Ltd., Hoboken, New Jersey, USA (2019)

[33] Cooper, S., Khatib, F., Treuille, A., Barbero, J., Lee, J., Beenen, M., Leaver-Fay, A., Baker, D., Popović, Z., players, F.: Predicting protein structures with a multiplayer online game. Nature **466**, 756–760 (2010) https://doi.org/10.1038/nature09304

[34] Kawrykow, A., Roumanis, G., Kam, A., Kwak, D., Leung, Wu, al.: Phylo: A citizen science approach for improving multiple sequence alignment. PLoS ONE 7(3): e31362 (2012) https://doi.org/10.1371/journal.pone.0031362

[35] Lee, J., Kladwang, W., Lee, M., Cantu, D., Azizyan, M., Kim, H., Limpaecher, A., Gaikwad, S., Yoon, S., Treuille, A., Das, R., null: Rna design rules from a massive open laboratory. Proceedings of the National Academy of Sciences **111**(6), 2122–2127 (2014) https://doi.org/10.1073/pnas.1313039111 https://www.pnas.org/doi/pdf/10.1073/pnas.1313039111

[36] Raddick, J., Bracey, G., Gay, P., Lintott, C., Murray, P., Schawinski, K., Szalay, A., Vandenberg, J.: Galaxy zoo: Exploring the motivations of citizen science volunteers. Astronomy Education Review **9** (2009) https://doi.org/10.3847/AER2009036

[37] Curtis, V.: Online citizen science games: Opportunities for the biological sciences. Applied & Translational Genomics **3** (2014) https://doi.org/10.1016/j.atg.2014.07.001

[38] Kultima, A., Piispanen, L., Junnila, M.: Quantum game jam – making games with quantum physicists, 134–144 (2021)

[39] Sawyer, B.: Serious games: Broadening games impact beyond entertainment. Computer Graphics forum **26**, (2007) https://doi.org/10.1111/j.1467-8659.2007.

01044.x

[40] Djaouti, D., Alvarez, J., Jessel, J.-P.: Classifying serious games: the g/p/s model. Handbook of Research on Improving Learning and Motivation through Educational Games: Multidisciplinary Approaches (2011) https://doi.org/10.4018/978-1-60960-495-0.ch006

[41] Ratan, R., Ritterfeld, U.: Classifying serious games. Serious games: Mechanisms and effects, 10–24 (2009)

[42] Rodríguez, Y.: Diseño de serious game para la enseñanza de la responsabilidad social en la educación superior. Revista Digital de Investigación en Docencia Universitaria **12** (2018) https://doi.org/10.19083/ridu.12.719

[43] Nagarajan, J.M. A.and Allbeck, Sood, A., Janssen: T.l. exploring game design for cybersecurity training. In Proceedings of IEEE Cyber, 256–262 (2012)

[44] Busch, P., Grabowski, M., Lahti, P.J.: Operational Quantum Physics. Lecture Notes in Physics. Springer, New York, NY (1995)

[45] Zeilinger, A.: Experiment and the foundations of quantum physics. In: More Things in Heaven and Earth, pp. 482–498. Springer, New York, NY (1999)

[46] MacFarlane, A.G.J., Dowling, J.P., Milburn, G.J.: Quantum technology: the second quantum revolution. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences **361**(1809), 1655–1674 (2003) https://doi.org/10.1098/rsta.2003.1227 https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2003.1227

[47] Deutsch, I.H.: Harnessing the power of the second quantum revolution. PRX Quantum **1**, 020101 (2020) https://doi.org/10.1103/PRXQuantum.1.020101

[48] Benioff, P.: The computer as a physical system: A microscopic quantum mechanical hamiltonian model of computers as represented by turing machines. J Stat Phys **22**, 563–591 (1980) https://doi.org/10.1007/BF01011339

[49] Deutsch, D.: Quantum theory, the church–turing principle and the universal quantum computer. Proc. R. Soc. Lond. A **400**, 97–117 (1985) https://doi.org/10.1098/rspa.1985.0070

[50] DiVincenzo, D.P.: Quantum gates and circuits. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences **454**(1969), 261–276 (1998) https://doi.org/10.1098/rspa.1998.0159 https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1998.0159

[51] DiVincenzo, D.P.: The physical implementation of quantum computation. Fortschritte der Physik **48**(9-11), 771–783 (2000) https://doi.org/10.1002/

1521-3978(200009)48:9/11⟨771::AID-PROP771⟩3.0.CO;2-E

[52] Ladd, T.D., Jelezko, F., Laflamme, R., Nakamura, Y., Monroe, C., O'Brien, J.L.: Quantum computers. Nature **464**(7285), 45–53 (2010)

[53] Nielsen, M.A., Chuang, I.L.: Quantum Computation and Quantum Information. Cambridge university press, Cambridge, UK (2010)

[54] Feynman, R.P.: Simulating physics with computers. Int J Theor Phys **21**, 467–488 (1982) https://doi.org/10.1007/BF02650179

[55] Zhou, Y., Stoudenmire, E., Waintal, X.: What limits the simulation of quantum computers? Physical Review X **10** (2020) https://doi.org/10.1103/PhysRevX.10.041038

[56] Marsh, S., Wang, J.B.: Combinatorial optimization via highly efficient quantum walks. Phys. Rev. Research **2**, 023302 (2020) https://doi.org/10.1103/PhysRevResearch.2.023302

[57] Grover, L.K.: A fast quantum mechanical algorithm for database search. In: Proceedings of the Twenty-Eighth Annual ACM Symposium on Theory of Computing. STOC '96, pp. 212–219. Association for Computing Machinery, New York, NY, USA (1996). https://doi.org/10.1145/237814.237866

[58] Robert, A., Barkoutsos, P.K., Woerner, S., Tavernelli, I.: Resource-efficient quantum algorithm for protein folding. Npj Quantum Inf. **7**(1) (2021)

[59] Jordan, S., Quantum, M.: Quantum Algorithm Zoo. https://quantumalgorithmzoo.org/

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

[61] Horowitz, M., Grumbling, E.: Quantum Computing. National Academies Press, Washington, D.C., DC (2019)

[62] Outeiral, C., Strahm, M., Shi, J., Morris, G.M., Benjamin, S.C., Deane, C.M.: The prospects of quantum computing in computational molecular biology. Wiley Interdiscip. Rev. Comput. Mol. Sci. **11**(1) (2021)

[63] Räsänen, S.: Kvanttirikko (eng. "Quantum Break"). https://www.ursa.fi/blogi/kosmokseen-kirjoitettua/kvanttirikko/. [Online, referred 12.03.2022] (2016)

[64] Kamen, M.: How real physics impacted time-travel game Quantum Break. https://www.wired.co.uk/article/quantum-break-interview-sam-lake. Accessed: 2020-04-23 (2016)

[65] Kohnle, A., Douglass, M., Edwards, T.J., D Gillies, A.: Developing and evaluating animations for teaching quantum mechanics concepts. European Journal of Physics **31**(6), 1441–1455 (2010) https://doi.org/10.1088/0143-0807/31/6/010

[66] Kohnle, A., Cassettari, D., Edwards, T.J., Ferguson, C., Gillies, A.D., Hooley, C.A., Korolkova, N., Llama, J., Sinclair, B.D.: A new multimedia resource for teaching quantum mechanics concepts. American Journal of Physics **80**(148) (2010) https://doi.org/10.1119/1.3657800

[67] Passante, G., Kohnle, A.: Enhancing student visual understanding of the time evolution of quantum systems. Physical Review Physics Education Research **15**(1) (2019) https://doi.org/10.1103/PhysRevPhysEducRes.15.010110

[68] Styer, D.F.: Common misconceptions regarding quantum mechanics. American Journal of Physics **64**, 31–34 (1996) https://doi.org/10.1119/1.18288

[69] Singh, C.: Student understanding of quantum mechanics. American Journal of Physics - AMER J PHYS **69** (2001) https://doi.org/10.1119/1.1365404

[70] Singh, C.: Transfer of learning in quantum mechanics **790**, 23–26 (2005) https://doi.org/10.1063/1.2084692

[71] Singh, C., Belloni, M., Christian, W.: Improving students' understanding of quantum mechanics. Physics Today **59**, 43–49 (2006) https://doi.org/10.1063/1.2349732

[72] Singh, C.: Student difficulties with quantum mechanics formalism. AIP Conference Proceedings **883**, 185–188 (2007) https://doi.org/10.1063/1.2508723

[73] Singh, C.: Student understanding of quantum mechanics at the beginning of graduate instruction. American Journal of Physics - AMER J PHYS **76**, 277–287 (2008) https://doi.org/10.1119/1.2825387

[74] Zhu, G., Singh, C.: Surveying students' understanding of quantum mechanics in one spatial dimension. American Journal of Physics **80**, 252–259 (2012) https://doi.org/10.1119/1.3677653

[75] ScienceAtHome: Games to lower the barrier of entry into the quantum world by giving everyone the capability to contribute to quantum research. https://www.scienceathome.org/quantum/games/

[76] QPlayLearn: An online platform designed for interactive learning in quantum physics. http://qplaylearn.com/. Accessed: 2023-03-17 (2020)

[77] HelloQuantum: A game for introducing basics concepts in quantum computing. https://helloquantum.mybluemix.net/. Accessed: 2023-03-17 (2010)

[78] Cataloglu, E., Robinett, R.: Testing the development of student conceptual and

visualization understanding in quantum mechanics through the undergraduate career. American Journal of Physics - AMER J PHYS **70**, 238–251 (2002) https://doi.org/10.1119/1.1405509

[79] Zhu, G., Singh, C.: Improving students' understanding of quantum mechanics via the stern-gerlach experiment. American Journal of Physics - AMER J PHYS **79**, 499–507 (2011) https://doi.org/10.1119/1.3546093

[80] Keebaugh, C., Marshman, E., Singh, C.: Improving student understanding of fine structure corrections to the energy spectrum of the hydrogen atom. American Journal of Physics **87**, 594–605 (2019) https://doi.org/10.1119/1.5110473

[81] Müller, R., Wiesner, H.: Teaching quantum mechanics on an introductory level. American Journal of Physics - AMER J PHYS **70** (2002) https://doi.org/10.1119/1.1435346

[82] Anupam, A., Gupta, R., Gupta, S., Li, Z., Hong, N., Naeemi, A., Parvin, N.: Design challenges for science games:. Int. J. Des. Learn. **11**(1), 1–20 (2019)

[83] Ahmed, S.Z., Weidner, C.A., Jensen, J.H.M., Sherson, J.F., Lewandowski, H.J.: Student engagement and learning with Quantum Composer. arXiv:2104.13260 [physics.ed-ph]. Accessed: 2022-05-24 (2021)

[84] Ahmed, S.Z.: Quantum Games and Simulations: Applications in Education, Outreach and Research. [Thesis (PhD)] (2021)

[85] Sørensen, J., Pedersen, M., Munch, M., Haikka, P., Jensen, J., Planke, T., Lieberoth, A., Sherson, J.: Exploring the quantum speed limit with computer games. Nature **532**(7598), 210–213 (2016) https://doi.org/10.1038/nature17620

[86] Heck, R., Vuculescu, O., Sørensen, J., Zoller, J., Andreasen, M., Bason, M., Ejlertsen, P., Elíasson, O., Haikka, P., Laustsen, J., Nielsen, L., Mao, A., Müller, R., Napolitano, M., Pedersen, M., Thorsen, A., Bergenholtz, C., Calarco, T., Montangero, S., Sherson, J.: Remote optimization of an ultracold atoms experiment by experts and citizen scientists. Proceedings of the National Academy of Sciences **115**, 201716869 (2018) https://doi.org/10.1073/pnas.1716869115

[87] Jensen, J., Gajdacz, M., Ahmed, S., Czarkowski, J., Weidner, C., Rafner, J., Sørensen, J., Mølmer, K., Sherson, J.: Crowdsourcing human common sense for quantum control. Physical Review Research **3** (2021) https://doi.org/10.1103/PhysRevResearch.3.013057

[88] Cong, S.: Control of Quantum Systems. Theory and Methods. Wiley Sons, Singapore (2014)

[89] Brif, C., Chakrabarti, R., Rabitz, H.: Control of quantum phenomena: past, present and future. New Journal of Physics **12**(7), 075008 (2010) https://doi.

org/10.1088/1367-2630/12/7/075008

[90] Mabuchi, H., Khaneja, N.: Principles and applications of control in quantum systems. International Journal of Robust and Nonlinear Control **15**, 647–667 (2005) https://doi.org/10.1002/rnc.1016

[91] Koch, C.: Controlling open quantum systems: Tools, achievements, and limitations. Journal of physics. Condensed matter : an Institute of Physics journal **28** (2016) https://doi.org/10.1088/0953-8984/28/21/213001

[92] Collaboration", T.B.: Challenging local realism with human choices. Nature **562** (2018) https://doi.org/10.1038/s41586-018-0489-0

[93] Simon J Devitt, K.N. William J Munro: Quantum error correction for beginners. Reports on Progress in Physics **76**(7), 076001 (2013) https://doi.org/10.1088/0034-4885/76/7/076001

[94] Devitt, S.: Programming quantum computers using 3-d puzzles, coffee cups, and doughnuts. XRDS: Crossroads, The ACM Magazine for Students **23** (2016) https://doi.org/10.1145/2983545

[95] Wootton, J.R.: Getting the public involved in quantum error correction. Proceedings of GSGS'17, 1712–09649 (2017) https://doi.org/arXiv:1712.09649v1

[96] Glaser, S., Tesch, M., Glaser, N.: SpinDrops. https://spindrops.org/. Accessed: 2022-05-25 (2018)

[97] Garden, Q.: Quantum Garden is an interactive art installation demonstrating key concepts of quantum physics. http://quantum.garden. Accessed: 2023-03-17 (2018)

[98] QPlayground: An online webGL version of Quantum Playground, an interactive quantum simulation platform. https://qplaylearn.com/games/quantum-state/quantum-playground/index.html (2020)

[99] Baumgarten, R.: Quantum Jungle. https://wobblylabs.com/projects/quantumjungle. Accessed: 2023-03-17

[100] Wootton, J.R.: Benchmarking near-term devices with quantum error correction. Quantum Sci. Technol. **5**(4), 044004 (2018)

[101] Wootton, J.R.: Benchmarking near-term devices with quantum error correction. Medium **5** (2018)

[102] Wootton, J.R.: Hello Quantum: Taking your first steps into quantum computation. https://medium.com/qiskit/hello-quantum-2c1c00fe830c. Accessed: 2020-01-13 (2018)

[103] Microsoft: Learn at your own pace with Microsoft Quantum Katas. https://cloudblogs.microsoft.com/quantum/2018/07/23/learn-at-your-own-pace-with-microsoft-quantum-katas/

[104] Google: Quantum AI, Quantum Chess Experiment. https://quantumai.google/cirq/experiments/quantum_chess. Accessed: 2023-03-17

[105] Wootton, J.R.: The History of Games for Quantum Computers. https://decodoku.medium.com/the-history-of-games-for-quantum-computers-a1de98859b5a. Accessed: 2020-01-13 (2018)

[106] Weisz, J.D., Ashoori, M., Ashktorab, Z.: Entanglion: A board game for teaching the principles of quantum computing. In: Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play. CHI PLAY '18, pp. 523–534. ACM, New York, NY, USA (2018). https://doi.org/10.1145/3242671.3242696 . http://doi.acm.org/10.1145/3242671.3242696

[107] IBMResearch: Entanglion, The world's first open source quantum computing board game. https://github.com/Entanglion/entanglion (2018)

[108] Wootton, J.R., Harkins, F., Bronn, N.T., Vazquez, A.C., Phan, A., Asfaw, A.T.: Teaching quantum computing with an interactive textbook. In: 2021 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 385–391 (2021). https://doi.org/10.1109/QCE52317.2021.00058

[109] Wootton, J.R.: Procedural generation using quantum computation. In: International Conference on the Foundations of Digital Games. FDG '20. Association for Computing Machinery, New York, NY, USA (2020). https://doi.org/10.1145/3402942.3409600 . https://doi.org/10.1145/3402942.3409600

[110] Wootton, J.R.: A quantum procedure for map generation. In: 2020 IEEE Conference on Games (CoG), pp. 73–80 (2020). https://doi.org/10.1109/CoG47356.2020.9231571

[111] Wootton, J.R., Pfaffhauser, M.: Investigating the usefulness of quantum blur. arXiv preprint arXiv:2112.01646 (2021)

[112] IndiQ: IndiQ Quantum Game Jam 2020. https://itch.io/jam/indiq-quantum-game-jam. Accessed: 2023-03-17

[113] Piispanen, L., Anttila, D., Skult, N.: Online quantum game jam. International Conference on Game Jams, Hackathons and Game Creation Events Proceedings (2023) https://doi.org/10.1145/3610602.3610610

[114] Piispanen, L., Anttila, D.: Aalto Quantum Games course nurturing the creative minds of physicists and game creators. https://youtu.be/yac3Os72nq4?feature=

shared. Accessed: 2023-05-11 (2022)

[115] Piispanen, L.: Designing quantum games and quantum art for exploring quantum physics. IEEE Conference on Games (CoG) (2023)

[116] Lee, C.F., Johnson, N.: Let the quantum games begin. Physics world **15**(10), 25 (2002)

[117] Du, J., Li, H., Xu, X., Shi, M., Wu, J., Zhou, X., Han, R.: Experimental realization of quantum games on a quantum computer. Phys. Rev. Lett. **88**, 137902 (2002) https://doi.org/10.1103/PhysRevLett.88.137902

[118] Jaakola, H.: Game: Escape from Quantum Computer. https://quantumgames.aalto.fi/game-escape-from-quantum-computer/. Accessed: 2023-03-17 (2021)

[119] Skult, N., Smed, J.: The Marriage of Quantum Computing and Interactive Storytelling, pp. 191–206 (2022). https://doi.org/10.1007/978-3-030-81538-7_13

[120] ScienceAtHome: Quantum Moves 2. https://www.scienceathome.org/games/quantum-moves-2/. Accessed: 2023-03-17

[121] Sels, D.: Stochastic gradient ascent outperforms gamers in the quantum moves game. Phys. Rev. A **97**, 040302 (2018) https://doi.org/10.1103/PhysRevA.97.040302

[122] Grønlund, A.: Algorithms clearly beat gamers at quantum moves. a verification. arXiv preprint arXiv:1904.01008 (2019)

[123] Esports Technologies, I.: Esports Technologies Files Quantum Computing Patent. https://www.prnewswire.com/news-releases/esports-technologies-files-quantum-computing-patent-301488342.html (2022)

[124] Togelius, J., Yannakakis, G.N., Stanley, K.O., Browne, C.: Search-based procedural content generation: A taxonomy and survey. IEEE Transactions on Computational Intelligence and AI in Games **3**(3), 172–186 (2011)

[125] Smith, A.M., Mateas, M.: Answer set programming for procedural content generation: A design space approach. IEEE Transactions on Computational Intelligence and AI in Games **3**(3), 187–200 (2011)

[126] Huang, J., Sharma, S., Ebrahimi, A., Cantwell, C.: Awesome Quantum Games. https://github.com/HuangJunye/Awesome-Quantum-Games. Accessed: 2023-03-17