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Quantum Tic-Tac-Toe - learning the concepts of quantum mechanics in a playful way

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ABSTRACT

Quantum mechanics is a complex matter. Nonetheless, given the impending arrival of quantum computers and the necessity for quantum programming abilities, more students should get acquainted with this subject. We provide a game-based learning approach based on Tic-Tac-Toe in a quantum modified version as a result of our study. We created a prototype to demonstrate and evaluate our assumptions using the design science research technique. Qualitative user feedback provided us with vital insights and shown that this game-based method helps to cope with quantum physics in a fun way. A majority of those who took part in the study stated that their interest in the subject had increased. However, for novices, it is necessary to follow them during the initial period of their training. The comments were quite helpful in optimizing the prototype. We found that our strategy, which included the use of a virtual opponent as well as the presentation of extra information about the quantum circuit, was more effective in helping participants comprehend quantum physics than earlier Tic-Tac-Toe-based learning settings.

1. Introduction

Quantum mechanics is frequently referred to be a new sort of physics due to the fact that its physical rules are fundamentally different from those of classical physics [26]. Superposition, entanglement, and quantum teleportation all operate differently than we are accustomed to in our Newtonian world. Explanations such as Schrödingers cat [24] are difficult to imagine, and even Einstein struggled to describe this phenomenon, referring to entanglement as “spooky activity at a distance” [8,13].

Recent years have seen a tremendous growth in the amount of knowledge collected about the world of quantum mechanics. Nonetheless, many people struggle to get started in quantum mechanics. For laypeople and even professional physicists, the concepts and their ramifications are difficult to grasp. With the growth of quantum computers, an increasing number of individuals are being compelled to deal with quantum computer programming, necessitating a working knowledge of quantum physics. This has been reported in various research papers, like [22,28], or [2].

Several attempts have previously been made to incorporate quantum logic and quantum circuits, which serve as the foundation for numerous quantum computers. Several of them make use of game theory and games to create a simple and appealing entry point, since they allow for a playful and practical approach [18,19,21,38]. Due to the enormous development and promise of this technology, it is becoming increasingly vital especially for young people to learn about quantum computing at an high-school age since they will be effected by this technology in future. It is critical for this generation in particular that the entrance point is intriguing and appealing. Nita et al. [29] argue that quantum literacy should be made more accessible to a broad group of learners. In their analysis of the secondary school quantum physics curricula of 15 nations, Stadermann et al. [37] observed that quantum physics and quantum mechanics are being introduced earlier and earlier. They also see the opportunity to discuss this complex topic in “unusual” ways. “Perhaps kids who grow up playing quantum games will acquire a visceral understanding of quantum phenomena that our generation lacks.” [34] p.14.

We propose a novel version of quantum Tic-Tac-Toe, as well as a learning environment that enables beginners to get an understanding of the behavior of individual quantum gates and their combinations in quantum circuits. The implications of quantum gate combinations become understandable when game tactics and move combinations are

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analyzed, as they are in chess. Exposure to these combinations repeatedly fosters intuitive comprehension of particular quantum gates.

We begin by introducing some essential concepts in quantum physics and quantum computing that will be discussed in the following section. Then, we review prior work on quantum Tic-Tac-Toe in order to create a baseline and classify our contribution. Following that, we will discuss our design science methodology and the prototype's implementation. Our study has been confirmed through interviews with experts and high-school students. Finally, we recap and discuss our accomplishments and provide a brief outlook.

1.1. Introduction to quantum mechanics and quantum computation

Quantum mechanics emerged mostly in the first part of the twentieth century. It is concerned with the tiniest particles and their properties, as well as the physical objects and quantities of microphysics. Quantum mechanical particles are so little that they are inaccessible to human senses. Quantum systems cannot thus be seen, felt, or tasted. In particular, quantum mechanics violates the conventional view that nature is always continually created and measurable.

The concept of quantum computation was proposed by scientist Richard Feynman, who suggested that quantum mechanical problems may be solved by computers that use quantum mechanics' principles. Additionally, the decreasing size of computer components has aided in the creation of quantum computers. It is foreseeable that there will be components the size of individual atoms. Here, conventional physics principles no longer apply, and one must engage in quantum mechanics. A detailed description of quantum computation, including a description of the physical principles, can be found in [26].

Due to quantum mechanics, the logic of ordinary computers that use boolean algebra cannot be applied to quantum computers. A conventional computer does calculations using bits, a logical, binary state with just two potential values. These variables can be classified as true or false, active or inactive. They are, however, most frequently expressed as **1** or **0**. In comparison, a quantum computer operates on the basis of so-called qubits ("quantum bits"). A qubit, unlike a conventional bit, does not adopt a single state of 1 or 0, but rather a linear combination of these states. This linear combination of states is also called "superposition".

Quantum gates are used as elementary operations on these qubits in some types of quantum computers. Unlike digital gates, quantum gates are not devices. They may be viewed as manipulations of a qubits' state (spin). This procedure modifies the ground state of a qubit. To have a better understanding, it is necessary to be familiar with the following quantum gates:

X gate: The Pauli X gate, or X gate, is a single-qubit gate, that operates on a single qubit (see Fig. 1). The X gate inverts the amplitude of the corresponding base state $|0>$or $|1>$to reverse the state vector of a qubit. As a result, the Pauli X gate is frequently referred to as a bit flip gate since it performs the same function as the NOT gate in classical logic gates.
ID gate: The identity gate, abbreviated ID gate, operates on a single qubit and maintains the qubit is perspective state, thereby preserving the spin. (see Fig. 2).
Hadamard gate: The Hadamard gate, often known as the H gate, is also a single-qubit gate (see Fig. 3). The gate elevates the base state $|0>$or $|1>$into a superposition of the two potential states. The Hadamard gate is inverse to itself. As a result, it reverses itself when applied again.

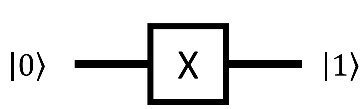

Fig. 1. X gate.

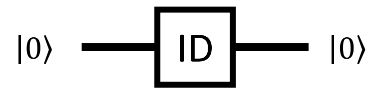

Fig. 2. ID gate.

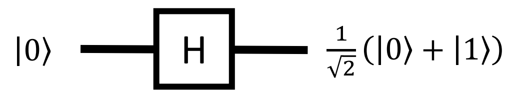

Fig. 3. Hadamard gate.

CNOT gate: The CNOT gate operates on two separate qubits, a control and a target qubit. When the qubits are in their base states of $|0>$or $|1>$, they act like conventional bits. The gate is quite easy and intuitive to grasp in this condition. When the base state of the first qubit is $|1>$, the CNOT gate executes a NOT operation on the second qubit (see Fig. 4). However, if the first qubit is base state is $|0>$, the base state of the second qubit remains unchanged. We employ the CNOT gate in conjunction with the superposition which is also known as Bell state (see Fig. 5). The Bell state will be explained later.

A quantum circuit is a combination of different quantum gates applied in sequence. It can be considered as a kind of computer program describing various manipulations of basic states of different qubits.

As previously stated, quantum mechanical phenomena are difficult to comprehend when seen through the lens of a Newtonian universe. As [22] and [28] indicate, this is especially true for STEM (Science, Technology, Engineering, and Mathematics) education. The following three principles are of paramount importance:

Superposition: the ability of a quantum particle to exist in two states simultaneously.
Entanglement: is the phenomena in which distant components of a quantum system exhibit unexplained connections. In this scenario, the state of the other component is influenced by the state of one component.
Collapse: The process through which a system's quantum states are reduced to classical states. When we measure the quantum circuit and thereby decrease the system, collapses occur. It is important to recognize that the state of qubits can be determined solely by measurement. At this time, the state collapses into a base state of either $|0>$ or $|1>$. The state of the qubit is destroyed during this operation and cannot be recovered unless by reapplying the quantum gates in the prior manner.

Our learning environment intends to teach these principles in a playful way.

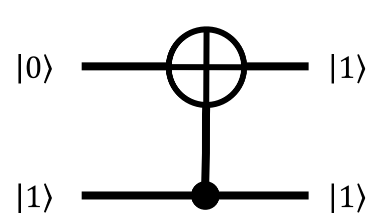

Fig. 4. CNOT gate.

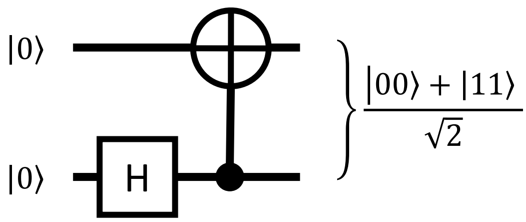

Fig. 5. Bell gate.

1.2. Related work

Several research publications on teaching quantum mechanics utilizing a game-based and inquiry-based learning (IBL) method have been published in recent years. Nita et al. [28] [29] present Quantum Odyssey, a puzzle based approach. They demonstrate that using puzzle games to illustrate physical events is particularly effective in explaining specific physical phenomena. The research of [19] evaluates several games in quantum game jams. One important result is that time must be set aside to introduce certain quantum mechanics fundamentals. Another facet of the web-based game learning environment is discussed in [20], which focuses on the advantages of using such environments for online learning. Many children were compelled to learn online, especially during the COVID pandemic. Self-learning and inquiry-based learning are made possible by web-based games with single-player modes, which are well-suited to remote education. Perkowski and Liu [31] also emphasizes the importance of this fact. Further suggestions for quantum mechanics learning games can be found in [3,5,6,11,30], or [4]. Some of the proposed learning environments, such as the VR learning area presented in [14], are comprehensive, sophisticated, and not suitable for online learning. A comprehensive overview of available quantum games and learning tools can be found in [36]. Different levels of complexity and target groups are addressed. Nevertheless, there are only a few approaches for high school students, like [21].

1.2.1. Tic-Tac-Toe as learning game

Games like Tic-Tac-Toe that are strategic but still simple to understand are ideally suited for online learning, and there have been various attempts to use this game to teach quantum mechanics. Tic-Tac-Toe is an ancient, basic game with origins dating all the way back to the 12th century BC. Without rotations and flips, there are just 5478 distinct game scenarios, which is a trivial amount of complexity in comparison to, say, chess. It is readily demonstrated that both players may force a draw, which rapidly renders the game “boring”. Our analysis of possible game types quickly led us to quantum Tic-Tac-Toe. This game, with its simple structure and high familiarity, provides the ideal environment to explain more complex mechanisms. Furthermore, the occupation of individual field and the necessary strategic considerations accommodate the quantum mechanical processes. By introducing quantum movements into the regular game of Tic-Tac-Toe, individual players’ chances of victory can be increased through the use of specific quantum tactics. Thus, by incorporating quantum game theory, Tic-Tac-Toe is transformed into a strategically compelling game.

Quantum Tic-Tac-Toe is played by players X and O on the same field as traditional Tic-Tac-Toe. Unlike classical Tic-Tac-Toe, quantum Tic-Tac-Toe employs quantum movements, which explains why quantum Tic-Tac-Toe retains features such as superposition, entanglement, and collapse. This distinguishes quantum Tic-Tac-Toe from classical Tic-Tac-Toe and complicates it, while also making it more intriguing. By playing quantum Tic-Tac-Toe, one is compelled to explore quantum mechanics and, as a result, learn the underlying mechanisms.

1.2.2. Existing quantum Tic-Tac-Toe variants

In 2002, Goff et al. [10] published the first version of quantum Tic-Tac-Toe. Their game was designed to assist students in transitioning from classical to quantum mechanical thinking. The study proposes a technique to understanding quantum mechanical processes using a game by introducing entanglement, cyclic entanglement, and collapse into a classical state. This original concept is not applicable to quantum computers or quantum gates, as in Goff’s concept the player can interactively control how a superposition collapses. Likewise, Persson and Waters [32] reported this issue. It is only a metaphor for the superposition, entanglement, and collapse phenomena. Their concept is certainly appealing to university-level students with prior expertise. It also offers very little guidance for inexperienced users.

Recently, Knight and Qualls [18] conducted a pilot study incorporating Tic-Tac-Toe into an online learning package. They used an implementation of the version of Goff et al. [10]. Although they have conducted a preliminary study with university students and created a rudimentary learning environment, their approach does not allow for independent learning by students or even high school students. In their outlook, they revealed that there is room for improvement in “how to best present the topics in educational-yet-entertaining manner”. In their games, there is a shortage of virtual opponents, such as AI-based players, who would aid in self-learning which is indicated by them.

Nagy and Nagy [25] provide a revised definition of quantum Tic-Tac-Toe, as do Sagole et al. [35]. The purpose of [25] is to demonstrate that a quantum player may outsmart a classical adversary with a specified probability. They created their version for implementation on a quantum computer, where the initial setup of the board superpositions all fields using Hadamard gates (H gates). While the classical player may view only single fields, the quantum player can choose between observation (measurement) of a field and entanglement through a CNOT operator. The introduction of superposition introduces a random aspect that, although beneficial for proving the quantum player’s advantage, complicates the explanation of the underlying quantum mechanical processes. Additionally, the game’s enjoyment is diminished, since the random impact tends to obstruct strategic considerations. Sagole et al. [35] modify this strategy significantly by putting the relevant qubit into a specified state upon measurement through an X gate or identity gate (collapsing). Additionally, they alter the entanglement in such a way that, depending on the control qubit is measuring, both qubits receive the same value. Thirdly, they enable both players to execute both conventional and quantum maneuvers. Both approaches address quantum game theory from a research standpoint and are not intended to be utilized in a classroom setting to teach students or high school students about quantum mechanical phenomena.

We examined the versions of Nagy and Nagy [25] and Sagole et al. [35] in detail and implemented them as prototypes during our investigation. However, in the context of our attempt to showing quantum methods, these game variations have the critical disadvantage of relying heavily on Hadamard gates for initialization (H gates). This introduces an additional random element. In Nagy’s approach, the benefit of a quantum strategy may be proved, but not convincingly and accessible for high-school students.

A recent study from Chiofalo et al. [7] used the implementation available on https://www.quantumtictactoe.com/(accessed-on-3-January-2023) described in [27] to analyse the learning and understanding of high-school students. The research was conducted with twenty students in 2022. The findings of this study are highly encouraging and consistent with our own. However, the used implementation of Tic-Tac-Toe does not create a connection between the taught concepts and a feasible implementation as a quantum circuit utilizing quantum gates.

Table 1 shows a comparison of the existing quantum tic-tac-toe variants. Some of them vary significantly in their method of operation, implementation, and target audience.

Table 1
Comparison of the main tic-tac-toe variants from the literature along with the solution presented in this paper.

	Goff [9]	Nagy et al. [25]	Sagole et al. [35]	Chiofalo et al. [7]	our solution
Implementable as quantum circuit	no	yes	yes	no	yes
Quantum principles	Superposition, entanglement, collapse	Superposition, entanglement, collapse	Superposition, entanglement, collapse	Superposition, entanglement, collapse	Superposition, entanglement, collapse
Quantum gates	none	X, ID, CNOT	X, ID, CNOT	none	X, ID, H, CNOT
Preallocation of gates	none	H	H	none	$\|1>$
Aim of the solution	Educate quantum principles	Advantage of quantum player	Show quantum strategies	Educate quantum principles	Educate quantum principles
Target level	University	University	University	High school	High school
Quantum circuit	no	yes	yes	no	yes
Virtual opponent	no	no	no	yes	yes
Learning environment	no	no	no	no	yes

1.3. Research questions

Quantum mechanics is difficult to comprehend yet crucial for high school students, according to Markus et al. [22], Nita et al. [28], and Angara et al. [1]. This importance is growing more and more with the stronger influence of quantum computers. The use of game-based learning environments is an excellent way to fill this void and instruct this difficult and dry subject matter. The literature review showed that existing game-based systems are still difficult to understand and very theoretical. There is a necessity for self-learning approaches that are simple and broadly available and give virtual opportunities, which is a vital component of online education. Our research focuses exactly on this topic. We derived the following research questions from the shortcomings described in the literature.

1.3.1. Research area 1: Implementation of a strategic, yet intuitive, game that enables quantum simulations on a modest computer.

RQ1.1: *Can the quantum Tic-Tac-Toe game be implemented as a simple web application without installation?*
This research question is inspired by the fact that several writers, such as Perkowski and Liu [31] and Li et al. [20], emphasize the significance of easy online access to learning games in an era where self-learning has become increasingly important. This research question is addressed by the prototype using a design science approach.
RQ1.2: *Can the quantum Tic-Tac-Toe game run on minimal infrastructure or even a mobile device?*
In order to support all students and also to allow self-learning, the game should run on a minimal infrastructure. Angara et al. [1] mentioned this as a relevant aspect. This research question is also addressed by the prototype.

1.3.2. Research area 2: Implementation of a virtual opponent, such as an AI (artificial intelligence) adversary, that employs a range of diverse tactics.

Knight and Qualls [18] proposes in their perspective for future research that a virtual opponent might increase pupils' motivation to play independently. This concept might also facilitate learning via inquiry (IBL).

RQ2.1: *What algorithms should be used to implement a sophisticated yet efficient and resource-efficient adversary?*
Based on RQ1.1 and RQ1.2, all virtual opponents should be resource-efficient. At the same time, the complexity of the moves should be high enough to make the game fun. This research question is addressed by the literature review and the prototype using the design science approach.
RQ2.2: *How can the virtual opponent implement different strategies?*
[12] emphasizes the significance of creating many tactics during the computer game-based learning process. An artificial adversary should facilitate this procedure by offering varied strategies during the game. This research question is also addressed by the prototype.

1.3.3. Research area 3: Design of a stimulating and encouraging learning environment that satisfies the above research areas.

RQ3.1: *Does the learning environment enable high school students to comprehend quantum mechanics more thoroughly?*
Quantum mechanics is a subject that must be taught in a manner that is both engaging and simple to comprehend, as stated in a number of publications noted in Section 1.2, like in [29]. The game-based method should facilitate this. This was verified with the help of user interviews.
RQ3.2: *How does a learning concept have to be structured so that the students get the greatest benefit from it?*
Gros [12] emphasizes the necessity of a concept of structured learning. She proposes four types of actions: exploration, reflection, activity, and discussion. The pedagogical approach is considered very relevant. Our learning concept was designed together with experts and verified using expert and user interviews.

2. Method

2.1. Research method and procedure

In our research, we used the design science research technique described in [15,17], and [33], a qualitative research approach. We defined the problem space with its involved players, organizational structures, and technology structures by assessing the target environment.

As previously mentioned, quantum mechanics is a highly complicated subject that is also gaining growing importance. As quantum computers become increasingly relevant to specific sorts of issues, an increasing number of researchers are examining this area of application. The problem space of our research addresses mainly high-school students. Nevertheless, it is also applicable for other educational levels like university students or career changers, who already possess a basic understanding of quantum mechanics and wish to practice and develop it. Within the confines of this problem space, we specified the research questions (RQs) formulated in Section 1.3 that our artifacts will attempt to address.

Starting with this baseline, we conducted a rigor cycle review of relevant work and prototyped the above-mentioned current solutions. We were able to more clearly identify current deficiencies and propose particular design suggestions as a result of this information. We conceived, developed, and tested our prototype iteratively throughout the design cycle. Each of the three iterations ended with a test. These testing comprised functional checks initially, followed by evaluations of the tactics used, and ultimately, user tests in conjunction with semi-structured interviews. To perform the survey in the form of interviews, the research questions have to be translated into interview questions.

RQ1.1, RQ1.2, RQ2.1, and **RQ2.2** will be addressed by the game prototype artifact, supported by literature review and user feedback, whilst **RQ3.1** and **RQ3.2** will be examined by user testing and interviews.

2.2. Tic-Tac-Toe - concept of the learning environment

We decided to utilize quantum Tic-Tac-Toe to demonstrate quantum mechanics in our learning environment. This is based on the literature research regarding quantum games and the in-depth evaluation of quantum Tic-Tac-Toe implementations described in 1.2. Playing is an important aspect in learning [16] and game theory is a serious discipline in economy and computer science [39]. As [23] stated, a game consists of "four defining traits: a goal, rules, a feedback system, and voluntary participation." Tic-Tac-Toe was chosen since the goal and the rules are simple to understand and practically everyone has played it in its original form. One gets quick feedback and the learning environment was designed in such a way that the feedback is comprehensible. We are all aware that if we avoid making any serious errors, the game will conclude in a draw. However, as demonstrated in [10], the quantum version of Tic-Tac-Toe is far more difficult. Our setting is fundamentally different from that of [10], in that we do not attempt to demonstrate the effect of entanglement in a Tic-Tac-Toe analogy, but rather to establish a relationship between quantum gates and move combinations in Tic-Tac-Toe. As a result, we provide the game board with the actual quantum circuit.

In a 9-qubit quantum circuit, all movements on the Tic-Tac-Toe board are converted into logical quantum gates. Thus, each qubit corresponds to one of the three fields on the 3x3 Tic-Tac-Toe board. The constraint to single movements per square, as used in classical Tic-Tac-Toe, permits quantum players to obtain an unfair advantage.[2] This significantly reduces the game's attractiveness. This resulted in the concept of permitting several movements inside a field. In our prototype, we allow three moves on a single field before locking the field. Once a field is locked, no further moves may be done to it.

We concentrated on four quantum motions that also serve as the most important quantum gates:

Identity gate or **ID gate**, is a kind of gate that maintains the real state of a qubit.
Pauli X gate or short **X gate**, which operates similarly to a classical NOT and inverts a qubit is status.
Hadamard gate, which creates a superposition when given a qubit is base state.
Quantum entanglement is achieved by employing the Bell state, which consists of two qubits and hence two fields on the Tic-Tac-Toe board.

When these gates are combined, entirely unique states are created, which is critical when dealing with quantum computers. For instance, the combination of two Hadamard gates eliminates the need for a gate between them, as seen in Fig. 6.

Additionally, knowing the so-called Bell state (see Fig. 7) is critical for analyzing quantum communication phenomena such as quantum teleportation. The Bell state is a synthesis of the H and CNOT gates. This unique type of entanglement between two qubits is characterized by the fact that both qubits always have the opposing spin. Einstein, Podolsky, and Rosen postulated the EPR effect in 1935, arguing that quantum entanglement violates the classical concept of local realism, which Einstein dubbed "spooky activity at a distance" in a famous statement.

Another critical feature that has been carefully considered is the

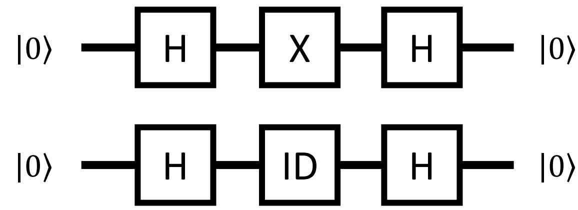

Fig. 6. Superposition.

instant at which the quantum circuit is measured. The state of a qubit collapses into a classical state that corresponds to the measurement result when it is measured. Occasionally, the state of the qubit is said to be annihilated. The superposition is resolved to either $|0>$or $|1>$in the case of a Hadamard gate. Prior to the measurement, no statement concerning the result can be made. This inevitably indicates that no winner can be identified prior to the measurement. Thus, the time of measurement establishes the time limit for declaring a winner. We chose the time of measurement after all fields had been visited at least once after designing and testing many versions. This also adds a new dimension to the game, as players must select not only which move to apply to which field, but also whether to continue playing previously visited fields or to end the game by visiting the last field.

Finally, we implemented an artificial adversary called a bot, which enables single players to compete against a virtual opponent. In comparison to classical Tic-Tac-Toe, which has several implementations, the majority of which employ a MiniMax[3] strategy, our quantum Tic-Tac-Toe is simply too complicated to make this possible. Particularly given that our learning environment should be accessible via a web browser. As a result, we developed a three-stage strategy inspired by chess. The game is separated into three stages: the opening, the middlegame, and the endgame. During the opening, fundamental moves (X gate or identity gate) are employed, allowing for the use of the MiniMax algorithm with a depth of nine. The MiniMax algorithm was expanded to include all potential movements in the middlegame. Additionally, this stage contained entanglement maneuvers (Bell state). The depth has to be decreased to two with this huge rise in complexity. The endgame begins when three unvisited fields remain. Again, a depth of two is used, and all maneuvers except entanglement are employed.

Unlike Nagy and Nagy [25] and Sagole et al. [35], we chose to pre-allocate the qubits with $|1>$by applying an X gate to all of the qubits. This provides a modest edge to player X (the starting player and the player for 1 in the fields). This advantage is intended, as this player is competing against an artificial opponent in a single player game. This is converted to a pre-allocation with $|0>$in expert mode to increase the difficulty of the game.

2.3. Learning methodology

As Gros [12] describes, a learning approach should be built around four distinct types of actions: exploration, reflection, activity, and conversation. Our environment is primarily focused on the first two actions: exploration and reflection, but also encourages and supports the other two via extra linkages and the recording of gaming sessions for subsequent study.

The joy of play and competitiveness stimulate experimentation. The match versus an artificial opponent, in particular, adds excitement to the game. It encourages experimentation and trying. Due to the complexity of the game, it cannot be solved via simple trial and error. Therefore, the individual gates of the qubits must always be meticulously studied. The

[2] see German thesis: Weingärtner, M., 2021. Quantencomputer – Ein Spiel mit Qubits. Maturaarbeit, Kantonsschule Baden, https://digital- twin.ch/quantum/Matura_Maurice_Weingaertner.pdf (accessed 17.1.2023)

[3] https://www.github.com/javacodingcommunity/TicTacToeAI-with-Minimax/blob/main/ticTacToeAI.py

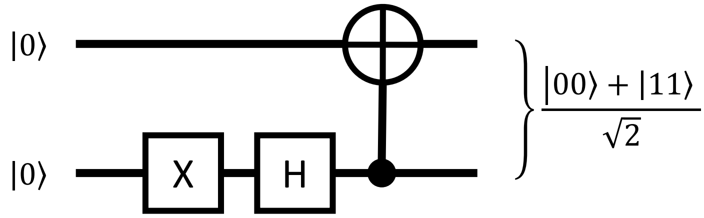

Fig. 7. Bell states.

player must mentally do the qubit measurement and determine which likelihood of achieving the desired result arises. By including tactical alternatives for each game circumstance, the many quantum effects may be discussed.

The persistent depiction of the quantum circuit, as well as the tracking of the move history, aid in reflection. This enables a player to recreate a certain game or circumstance. It is important to remember that some gate configurations include a random component. As a result of this random component, restarting a game might result in different outcomes.

2.4. Validation by using a prototype

To demonstrate practicality and acquire insight on learning success, we created a prototype of the above-mentioned concept. As noted earlier, this prototype is designed to run on a web browser and is thus written in HTML and Javascript. The quantum circuits are implemented using the Quantum Circuit Simulator Library.[4] This offers the necessary functionality as well as the ability to render a quantum circuit as a SVG picture (see Fig. 8).

The web user interface is straightforward and consistent in its design. Its primary objective is a high degree of self-explanatory. In addition, a help page introduces the basic quantum concepts. Figures 8 and 9 depict an illustration of the prototype where Fig. 9 is the lower part of the game page. The main gaming area, which is shown in Fig. 8, consists of the following major components: the selection of movements (switch = circled arrow, retain = arrow down, superposition = tilde, and entanglement = dot and crossed circle), the control buttons to select the option of using or not using the bot, the beginner or expert mode, and a new game, the Tic-Tac-Toe game board, and the corresponding quantum circuit. While playing versus the bot, a notice indicates the number of distinct versions it has attempted. 17,322 variants have been attempted in the game in Fig. 8.

The moves of the players are indicated by symbols placed on the game board's fields. Each participant is allocated a distinct color to distinguish their plays. This variety was created during the second improvement cycle. A playing field can be filled with no more than three movements. After this limit, the field becomes yellow and becomes unplayable (see Fig. 8, the top left field). Unplayed fields are denoted by a dark blue color and include the qubit number (in Fig. 8, the middle field, which is q4). The quantum circuit to the right of the game board is changed after each move to reflect the real game status.

For educational purposes, the beginner mode displays gate combinations and tactical information in the lower portion of the user interface (see Fig. 9). Together with the player's move history, this information may be used to analyze the player's games and design a winning strategy. It also aids in the comprehension of quantum concepts.

After experimenting with various different configurations, we settled on the following settings:

1. **Start of middlegame** if five unvisited fields remain.
2. **Start of endgame** if three unvisited fields remain.
3. **Depth of the MiniMax** is set to two for the middlegame and endgame to ensure a reasonable performance.
4. **Moves per field** is limited to three. Following this, the field is permanently set and cannot be altered.

After each field is played, the qubits are measured to decide the winner. Player **O** receives **|0>** measurement results, whereas player **X** receives **|1>**. Only during this procedure are the qubits in superposition collapsed, allowing for the determination of a value. As with traditional Tic-Tac-Toe, the winner is determined by the appearance of three identical symbols in a row. It is irrelevant whether these three classical states occur in a row horizontally, vertically, or diagonally. Four distinct outcomes are possible:

1. Player X possesses a row, but player O possesses none: This means that X has won.
2. Player O possesses a row, but player X possesses none: Thus, O has won.
3. Neither player has a row: The game is declared a draw.
4. A novel scenario is for both players to have a row: This is also considered a draw.

The following fictitious game sequence illustrates the course of the game depicted in Fig. 8 for illustrative purposes. This information is also available in the history section of Fig. 9. The setting is that the artificial opponent (the bot) is used and the game is in beginner mode. The fields are numbered 1 (top left) through 9 (lower right).

Player 1, the user (black), begins on field 1 with a switch move. Player 2, the bot (white), positions a switch in field 2. Field 1 is marked with a retrain (identity gate) by player 1. Player 2 plays a switch in field 3. Field 7 receives a superposition (H gate) from player 1. Player 2 makes use of an entanglement between fields 8 and 6 (CNOT). Player 1 likewise responds with an entanglement between fields 4 and 9 (CNOT). Player 2 makes the third move on field 1 and freezes the field with a switch.

If player 1 chooses a retain move in field 5 (middle field), then all fields will have been played and the quantum circuit will be measured.

We refer to the prototype's source code, which is made accessible to the public on Github[5], for more clarification.

2.5. Collecting data from interviews

In order to demonstrate the usability of the prototype and answer **RQ3.1** and **RQ3.2** we conducted semi-structured interviews with three user groups and provided them with the creation of a prototype artifact. After a brief introduction that varied based on the user groups (see below), we encouraged the interview partners to test out the game and participate in multiple iterations. Our first user group, *quantum mechanic specialists*, we had not to explain the quantum mechanical theories and

[4] https://www.npmjs.com/package/quantum-circuit

[5] https://github.com/timweing/quantum_tic-tac-toe - a playable version is available on https://www.digital-twin.ch/quantum/

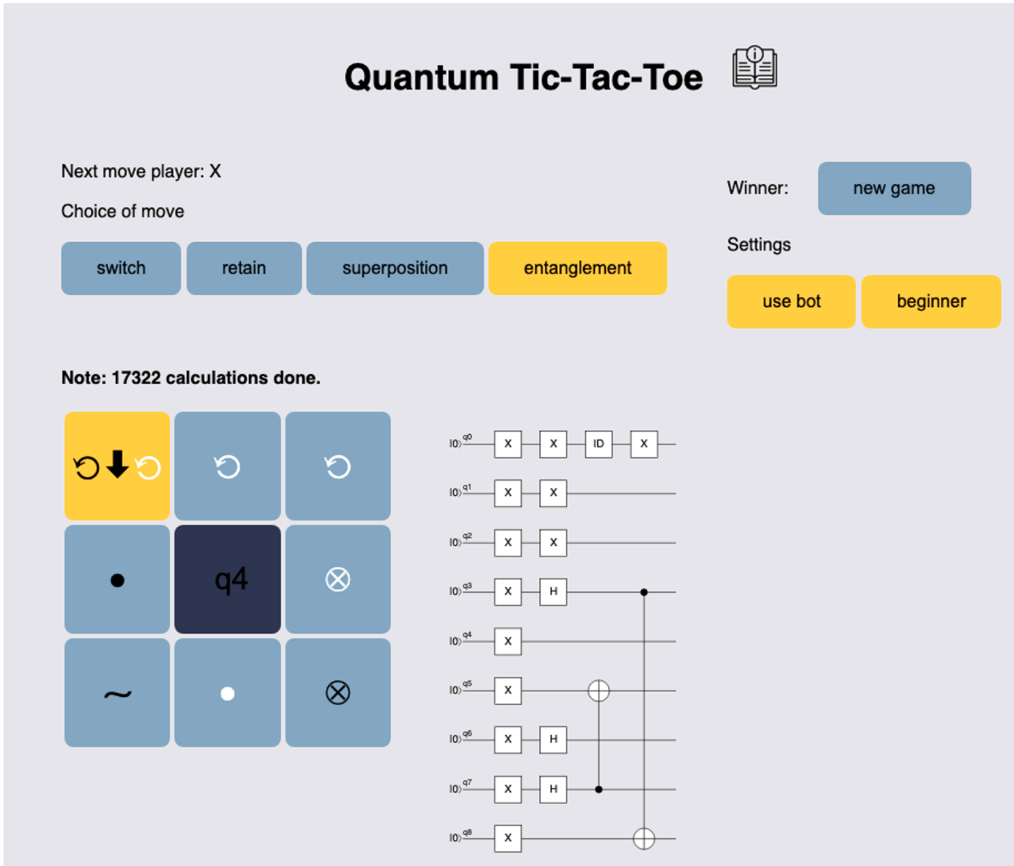

Fig. 8. Example of the prototype with the selection of the moves, the settings, the game field and the quantum circuit.

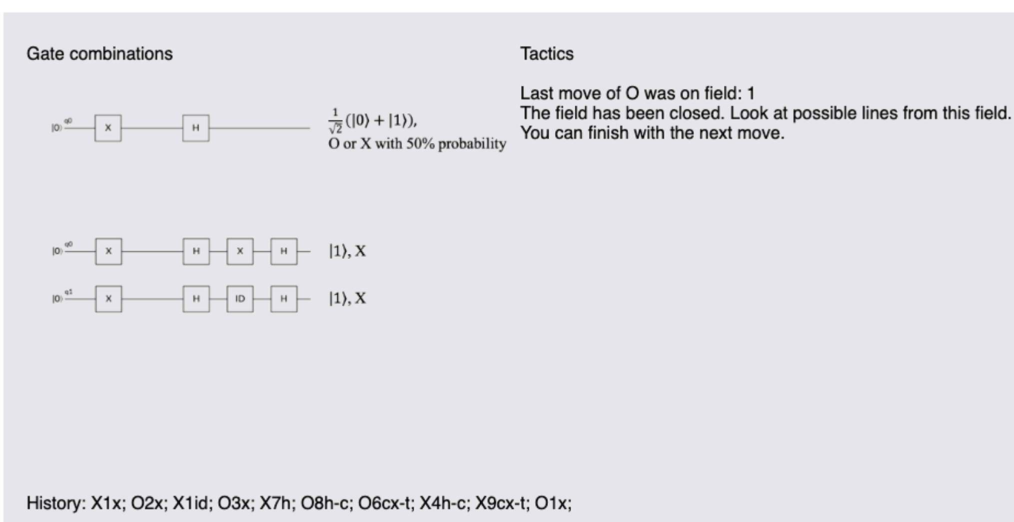

Fig. 9. Lower part of the prototype with the analysis of gate combinations, a suggested tactics and the history of moves. The first two are only visible in beginners mode.

quantum gates. The goal of the interviews with this group was to collect expert input on the implemented artifacts and iteratively enhance the prototype. The second user group, *people with an academic background*, was supposed to be a preliminary check on our assumptions and a feedback group on our interview questions. We provided them a brief overview of the game's fundamental principles and use. Our target audience, *high school students*, were guided through the usage of the game and obtained an introduction into the quantum mechanical basics. These interviews were conducted to provide qualitative feedback on our prototype and to confirm or reject our hypotheses.

Our major feedback group, high school students, were asked questions regarding three sections: the game and the website, the game understanding and enjoyment, and finally the added value generated. These sections are directly correlated to the research questions. The following questions have been asked:

Questions regarding the game and the website
Is the game easy to grasp, and are the descriptions adequate and clear? If not, then why?
Are the game options obvious and relevant? If not, then why?
What do you need in order to play the game?
Questions concerning the enjoyment of the game
Was it enjoyable to play? Why?
Was the game too easy or too difficult?
Were you able to defeat the bot, or did you lose at least once?
Does the bot assist you in comprehending and considering various tactics?
Is the display of qubits helpful in comprehending and considering a feasible tactic?
Questions regarding the additional value
Did the game help you understand quantum mechanics and quantum gates better? Why?
What are your thoughts on incorporating the game in your classes?
Would you want to continue playing it in future on your own?

3. Results

Our research resulted in the creation of a prototype and functional tests, as well as improvement cycles (see also appendix B). This prototype served as the foundation for addressing each of the research questions. During the last iteration, we gathered some critical feedback from users, which we included into the final version of the prototype.

Nine semi-structured interviews have been carried out with users from the described three groups. The following summarizes the major findings from those interviews:

Description of the game: Particularly newcomers to the subject struggled with the brief presentation of the game and the fundamentals of quantum computing. The description has been extended. A working knowledge of quantum computing is required, and we supplemented the literature.
Complexity of the game: The game was assessed as difficult by all interview partners. This was the game's goal: to encourage in-depth involvement with the subject.
Fun to play: This question was addressed in a variety of ways. Users who invested more time and effort rated the game as more enjoyable than those who completed only two or three games. This is further reinforced by an interviewee's comment that a deeper and longer connection with the game is a required condition.
Helpfulness of the bot: The AI or bot was deemed beneficial by a majority of interview partners. According to others, the fact that the bot repeats some moves makes it simpler to learn from these outcomes.
Visualization of quantum circuit: Additionally, the presentation of the quantum circuit was deemed beneficial if a longer engagement was approved.
Use in guided learning or self-learning: A critical question was whether the game should be utilized for guided learning or self-learning. The majority of interviewees encouraged using the game in a guided learning setting, owing to the game's intricacy and potential for frustration for new players. Following a guided phase, the second step was proposed to be self-learning.

A quantitative analysis of the answers regarding to the enjoyment and added value of the game over all nine user interviews showed the following results: Seven enjoyed playing the game. Eight described the game as challenging but doable. Five indicated that the game helped them understand quantum mechanics and quantum gates better. Also five wished if such a game would be embedded in physics lessons. Six could imagine playing the game on their own outside of a lesson.

In response to this feedback, we developed a learning concept for our application (see RQ 3.2):

1. Explain the principles of quantum physics, including superposition, entanglement, and the Bell state, in addition to the fundamental quantum gates.
2. Describe the quantum Tic-Tac-Toe game, its movements, beginner/expert mode, and tools such as history, quantum circuit, and strategies.
3. Allow students to play the game three times. Then, respond to any questions that emerged.
4. Allow the students to play the game five times in a row in order to gain their unique experiences. Discuss issues regarding functioning and inquire about their strategies.
5. Allow them to play alone and engage in regular group interactions.

We assessed this concept favourably with two students.

4. Discussion

Based on the prototype, functional tests, and improvement cycles, we were able to show that the chosen technology and software libraries were able to construct a functional and reliable web-based application. Feedback from our user groups emphasizes this finding.

How can the Tic-Tac-Toe game that is both strategic and easy to comprehend combine quantum computer simulations while operating on any infrastructure without requiring a substantial amount of installation, processing power, or hardware? Research area 1 dealt with the question of the implementation of an intuitive quantum Tic-Tac-Toe game that includes quantum simulations on a computer. The two research questions can be answered in the following manner:

RQ1.1: Can the quantum Tic-Tac-Toe game be implemented as a simple web application without installation?
We demonstrated that this is achievable through the implementation of the prototype using a regular web browser. The used libraries allowed us to display the quantum circuit at any time and to add further information according to the course of the game.
RQ1.2: Can the quantum Tic-Tac-Toe game run on minimal infrastructure or even a mobile device?
The implemented prototype operates in a standard web browser. No specialized hardware is necessary. The simulation of the quantum circuit, the virtual opponent, and the visualization even run on a mobile device, despite the fact that the prototype is not yet suited for mobile display.

Research area 2 focused on the virtual opponent implemented as an AI adversary. The two research questions in this area can be answered in the following manner:

RQ2.1: What algorithms should be used to implement a sophisticated yet efficient and resource-efficient adversary? *We utilized the MiniMax algorithms of varying depths and quantum moves to construct an effective yet formidable adversary. The operations are calculated in about 5 s, allowing for a fluid gaming. User feedback indicates that a virtual opponent offers several benefits. It was positively received by all of our participants.*
RQ2.2: How can the virtual opponent implement different strategies? *The three-phase division of the game into opening, middlegame, and endgame, each with several move variants, enables the virtual opponent to respond quickly and intelligently to player actions.*

Finally, research area 3 examined how to construct an exciting and encouraging learning environment that fulfills the aforementioned research goals.

RQ3.1: Does the learning environment enable high school students to comprehend quantum mechanics more thoroughly? *Yes, the described quantum Tic-Tac-Toe game in combination with the developed learning concept helps to develop a simpler, playful learning approach for* *quantum mechanics and quantum computing. The responses from our target audience demonstrated that the ideas of quantum mechanics could be presented in a more comprehensible manner, and many participants commented that they had a better understanding of concepts such as superposition as a consequence of playing the game. From the interviews, we can see that the students even attempted alternative strategies.*

RQ3.2: How does a learning concept have to be structured so that the students get the greatest benefit from it? *A guided introduction by an expert or teacher is a requirement. The expert will explain the fundamentals of quantum mechanics, demonstrate key features of the game, and support during the first game iterations in case of questions. From this point on, self-education is advised. Compared to existing approaches, our game is specifically designed to support high-school students during their learning experience.*

5. Conclusions, limitations and future research

Our research demonstrates that combining our version of quantum Tic-Tac-Toe with supporting learning features such as displaying the quantum circuit, introducing a virtual opponent, and presenting more information based on the game scenario increases the appeal and attractiveness of quantum mechanics to students. We provided a learning concept to use our application in a lesson for high-school students. This increases the motivation for self-directed learning in a stimulating setting. The game facilitates learning by utilizing a lighthearted approach and engaging players via competitive play. Our prototype demonstrated that implementation is feasible and that it is well received by a varied set of interviewees.

The user feedback also showed some limitations. In the beginning phases, it is crucial that learners not be left alone and that the game be utilized in conjunction with an introduction lesson. Students should be accompanied by an experienced person or given the opportunity to discuss thoughts in groups, especially during the initial period. Otherwise, the player’s displeasure is predestined.

As a result, we recommend integrating the game into a guided learning environment. Our next efforts will be directed at promoting the prototype in as many learning environments as possible. Only with further feedback from various teachers and students is it feasible to develop an enhanced learning tool. Our goal is to provide as many novices as possible with a pleasant introduction to quantum mechanics and quantum computer programming.

CRediT authorship contribution statement

Maurice Weingärtner: Conceptualization, Software, Visualization, Writing – original draft. **Tim Weingärtner:** Software, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. User testimonials

During the interviews, anonymity was assured for the interviewees. Nonetheless, we would like to provide some quotations and user testimonials for our target audience below.

- “The game itself is understandable. It took me a few tries to even understand what was happening, but over time I understood what was happening on the field. That doesn’t mean I always saw through whether I was in a good or bad position, though.”
- “The game was not much fun in the first 2–3 rounds, because I understood absolutely nothing despite the theory. With time, however, I was able to understand better and better what kind of condition the playing field was in. After this realization it was a lot of fun. Meanwhile I have reached a point where I have always started a round to try something.”
- “Yes, it was fun. The fact that there is the possibility to play with a bot made the game more fun than trying out the quantum gates in a quantum tic-tac-toe.”
- “The game was a bit too complex, as the bot still defeated me even in Beginner mode after playing several times, which was a bit frustrating. It would be good if there was a worse bot or a mode where you can see how the field is currently occupied (X or O).”
- “For me the display of the qubits was understandable in any case. I used it mainly to check again how the sequence of the individual gates is and to understand in which state the field is.”
- “I had a rough overview of quantum computing, but I didn’t know any specific gates and how they worked. With the game, I could directly look at the results of each gate and try around.”
- “I can see using the app in class very well, especially since it is much more interactive than the classes we have today. It certainly would have helped with understanding quantum physics for the reason that we have also touched on the subject in class before.”

Appendix B. Improvement cycles of the prototype

B1. Improvement cycle 1

The initial version of the game only supported two players. Through input from the experts and our own utilization, it became immediately apparent that a virtual opponent gave a decisive edge. This was later verified by several comments.

B2. Improvement cycle 2

The following modifications and enhancements were recommended by various specialists and academics:

1. Different coloring of the fields depending on the turn of the two players.
2. Performance improvement of the virtual opponent.
3. Displaying the quantum circuit and the reference from each field to the corresponding qubit.
4. Improvements to the description.

B3. Improvement cycle 3

The final improvement cycle included the following modifications and enhancements:

1. Proposed strategies.
2. Displaying the history.
3. Introducing different levels of complexity

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.caeo.2023.100125.

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