Using Game-Based Learning and Quantum Computing to Enhance STEAM Competencies in K-16 Education

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***Abstract*—Quantum computing is an emerging and quickly expanding domain that captivates scientists and engineers. Recognizing the limitations of conventional educational approaches in adequately preparing individuals for their incursion in this area, this research introduces a novel board game called "Qubit: The Game," whose objective is twofold: 1) to foster enthusiasm for quantum computing and 2) to enhance comprehension of fundamental notions within this discipline. This document provides explanations regarding the rationale behind selecting a board game format, the game's design and mechanics, as well as the methodology followed during its development. Furthermore, it contains a first analysis conducted to assess the impact of the designed game, on the perception, interest and fundamental notions of quantum computing among K-16 students. The outcomes from this research unequivocally demonstrate that the devised game serves as a potent instrument in cultivating enjoyment and facilitating the understanding of essential knowledge in a topic as intricate as quantum computing. In fact, the effectiveness of this game also highlights its potential to introduce learners to different STEAM-related topics.**

***Index Terms*—Game-based learning, K-16 education, quantum computing, STEAM-related topics.**

I. Introduction

THE FIELD of quantum computing is currently booming, so it is bound to have great relevance in the near future, due to its potential applications in various domains. One such domain is cybersecurity, which needs to be reimagined in light of the threat posed by the advent of quantum computers capable of breaking the cryptographic algorithms that support today's secure information technologies. Nevertheless, quantum computing presents a formidable learning challenge. Many individuals find it difficult to understand its basic concepts due to the scarcity of accessible quantum computing systems and its inherently theoretical nature that contradicts intuitive understanding and conventional models of thinking.

The objective of this research is to facilitate individuals' adaptation to the post-quantum era by addressing the learning barriers associated with this complex field. Thus, the main aim is to offer learning support through a game-based resource that enables K-16 students to navigate the intricacies of quantum computing and other STEAM-related topics effectively.

Extensive research in the field of mathematics and physics education reveals that a significant number of students find it hard to comprehend complex notions, particularly those associated with quantum mechanics. Several studies have consistently demonstrated that learners require a sense of engagement and interest in a topic for effective learning to occur [1]. Furthermore, it is widely acknowledged that significant and genuine learning is achieved incrementally as students manage and absorb the significance of new received data. To this end, educational games, particularly board games, have been successfully employed many times to take advantage of their unique potential to combine features related to knowledge, emotion and interaction with the learning process [2].

Indeed, different studies have confirmed the efficacy of game-based learning when compared to classical approaches. First, it stimulates a higher level of student enjoyment, capturing their attention and fostering active participation. Second, although it may require additional time investment, the depth of understanding and assimilation of concepts tend to be significantly enhanced. These findings underscore the value of incorporating game-based approaches as an effective means of promoting meaningful learning experiences.

In this article, a novel approach is presented in the form of "Qubit: The Game," a groundbreaking game designed to provide an engaging avenue for introducing basic notions pertaining to quantum states and state transitions. This game offers an entertaining experience for two or more players through a set of three different card types related to the concepts of qubits, quantum gates, and projections, with the ultimate goal of building a binary key sequence.

A field study has been conducted to examine the impact of "Qubit: The Game" on several groups of K-16 students, yielding encouraging various findings that are presented in this article. One of the conclusions is that the game captivated K-16 students through an immersive and enjoyable experience. Additionally, the proposed game has been successfully demonstrated as a way to connect K-16 education with university research. In particular, it can be seen as a platform to practice essential computer skills and foster a mindset that recognizes computer science as a key competency and vital way of thinking for the future of the real world. Furthermore, it has the

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potential to be used for the development of different STEAM competencies among K-16 students, igniting their passion for STEAM related subjects, which is much needed in these times.

Therefore, within this game, students are introduced to the revolutionary world of quantum computing, giving them insight into future technologies that build on this innovative field. As they embark on a new learning path in quantum computing education, students discover its interdisciplinary and multidisciplinary applications, and witness its far-reaching impact across multiple domains.

This document encompasses the essential components of the proposed game, including its design, development, and field study. The main objective of the research has been to ensure a useful learning resource that can be used as a robust educational experience for K-16 education. Besides, special attention has been paid during the development of the proposal to the active promotion of scientific, computational and algorithmic thinking to foster these essential 21st century competencies for K-16 education.

The structure of this article is as follows. In Section II, an overview of relevant literature and related works in the field is provided. Section III presents an introduction to the quantum computing concepts addressed within the game. Extensive details regarding the design and mechanics of the proposed game are outlined in Section IV. Section V focuses on the pilot experience conducted with several groups of students, outlining various key findings from the study and initiating a brief discussion. Finally, Section VI is the concluding section that summarizes the main aspects of the proposal, and provides some final insights and open research lines.

II. Related Works

Within the existing bibliography, several approaches can be found that propose the introduction of quantum concepts either in the curricula or through different visualization and simulation tools. Unlike most of those proposals, which are unidirectional or digital, in the proposal defined in this article a deliberate choice was made to create a physical board game that requires face-to-face interaction within groups of students.

Prominent contributions to introduce the teaching of quantum computing at secondary education can be found in papers, such as [3], [4], [5], [6], [7], [8], [9], and [10]. Each of them approaches the subject from a distinct perspective and offers valuable insights.

Westfall and Leider [3] identified the most fundamental ideas and knowledge that needs to be understood in order for a high school student to start writing and running simple quantum computer programs.

Although quantum computing concepts are complex, it is possible to introduce them at early ages. For instance, the paper [4] proposes teaching quantum concepts in K-12 schools, and the works [5], [6], [7] describe several experiences delivering quantum computing courses for high-school students.

Furthermore, the paper [8] presents an approach tailored for secondary school students, which offers different instructional materials designed to enhance the educational and cultural dimensions of quantum computing. Also [9] and [10] introduce the basic concepts of quantum physics at a secondary school level by using classical mechanics and Web-based teaching modules, respectively.

Distinct from all aforementioned works, the research presented here does not focus on designing modules for curricular or extracurricular courses. Instead, this document introduces an educational game specifically designed for K-16 students, with versatile applicability in various contexts. It can be seamlessly integrated into formal courses as a valuable teaching tool or enjoyed as a recreational activity.

Proof that quantum computing can be used as a way to introduce STEAM concepts are the papers [11] and [12], which highlight the role of mathematics in the teaching of quantum physics at high school.

To design the game's cards proposed here, the authors drew upon their extensive expertise with IBM's Qiskit tool [13], renowned for its exceptional visualization capabilities. The literature contains numerous references to various approaches that employ interactive simulation and visualization tools for teaching quantum mechanics. Relevant works in this regard include [14], [15], [16], [17], [18], [19].

In [14], a collection of interactive simulations within the open-source GeoGebra environment is presented as a means to teach quantum physics. Furthermore, Singh [15] explored the use of interactive animations and simulations to improve student understanding of quantum mechanics and quantum information theory. Other publications propose specific tools for quantum visualization, such as PhET [16], QuILT [17], and QuVIS [18]. Finally, [19] is a textbook that guides instructors in teaching quantum mechanics using computer-generated animations.

It is important to note that the objective of this current work differs from the aforementioned references. While the focus of those works is primarily on teaching quantum mechanics through simulation and visualization tools, this study aims to introduce essential concepts of quantum computing through a board game.

Many software-based games have been proposed to present quantum concepts. "Schrödinger cat and hounds" [20] is a computer game to introduce concepts of quantum mechanics. The review [21] provides an extensive overview of quantum games and interactive tools, including many Web or mobile-based games, such as Particle in a Box [22], Psi and Delta [23], QPlayLearn [24], Virtual Lab by Quantum Flytrap [25], Quantum Odyssey [26], ScienceAtHome [27], and The Virtual Quantum Optics Laboratory [28]. Among all those games, Quantum Odyssey [26] deserves to be highlighted because it is a visually enhanced software game that assists in learning the creation and optimization of quantum algorithms for quantum computers. Besides, [29] is a software-based serious game for learning quantum computing concepts. Also, the paper [30] presents a game called The Quantum Computer Game, which allows players to help solve actual scientific challenges in the effort to develop a quantum computer.

Within the most relevant literature with respect to the present work, there are two noteworthy games that have been proposed for teaching quantum computing through physical games. On the one hand, Entanglion [31] is a board game designed to introduce fundamental concepts of quantum computing. On the other hand, a very recent paper [32] presents a card game in which the building blocks of a quantum computer can be experienced. In comparison with them, "Qubit: The Game" is a card game with a focus on introductory content suitable for various audiences. Besides, its purpose extends beyond education as it also aims to generate interest and enthusiasm for the subject. Feedback from a study conducted with K-16 participants indicates that both educational and attraction objectives have been successfully achieved.

III. Quantum Computing Fundamentals

A. Qubit

The smallest unit of information in classical computer science is called a bit. A bit can be in only one of two possible states, usually denoted by 0 and 1. However, in the quantum paradigm the basic unit of information is the quantum bit or qubit, which can be in any of the infinite possible linear combinations of the $|0\rangle$ and $|1\rangle$ basic states that form the computational basis, as is illustrated in (1), with $\alpha, \beta \in \mathbb{C}$ and $||\alpha||^2 + ||\beta||^2 = 1$

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,. \tag{1}$$

Thus, the $|0\rangle$ quantum state corresponds to $\alpha = 1$ and $\beta = 0$ while the opposite case occurs for $|1\rangle$.

B. Superposition

The word superposition applies to a state that cannot be represented by a single component, like the basis states, with respect to a specific basis [33]. In fact, as illustrated in (2) and (3), there exist two superposition states with respect to the computational basis, whose states lie in an equiprobable superposition of $|0\rangle$ and $|1\rangle$, since $||\alpha||^2 = ||\beta||^2 = (1/2)$

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \tag{2}$$

$$|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \tag{3}$$

These states can be considered basic, according to the so-called Hadamard basis $\{|+\rangle, |-\rangle\}$, considering the rest of possible states a superposition of them. For example, the states $|0\rangle$ and $|1\rangle$ are in an equiprobable superposition with respect to the Hadamard basis, as illustrated in

$$|0\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle) \tag{4}$$

$$|1\rangle = \frac{1}{\sqrt{2}}(|+\rangle - |-\rangle). \tag{5}$$

C. Bloch Sphere

To improve the visualization of the concept of superposition, the Bloch sphere is an intuitive visual representation of the qubit. The goal of this mathematical object is to represent in a 3-D space two complex numbers, each of them given by two real numbers. Considering two opposite states on the sphere as orthogonal states, it is possible to leave a missing dimension (see Fig. 1).

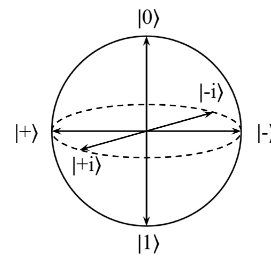

Fig. 1. Bloch sphere.

Therefore, a sphere of radius 1 and an arrow inside it pointing to a point on its surface are needed to represent the state of a qubit. The greater the arrowhead elevation, the higher the probability of observing the $|0\rangle$ state, whereas the lower the elevation, the higher the likelihood of obtaining the $|1\rangle$ state. This principle applies similarly to the horizontal axis, with the $|+\rangle$ and $|-\rangle$ states corresponding to left and right, respectively.

D. Quantum Gates

A quantum gate refers to a operation that can be implemented on the states of qubits. When it comes to gates applied to a solitary qubit, they can be envisioned as rotations of the qubit's state vector on the Bloch sphere. The gates involved in the suggested game encompass the Pauli gates X and Z, the Hadamard gate H, and the $SWAP$ gate.

1) Pauli-X: This gate is designed for a lone qubit and can be depicted as a π-radian rotation around the X axis on the Bloch sphere. This phenomenon occurs because the qubit state amplitudes are interchanged relative to the computational basis [see (6)]

$$\alpha\,|0\rangle + \beta\,|1\rangle \xrightarrow{G_X} \beta\,|0\rangle + \alpha\,|1\rangle\,. \tag{6}$$

Consequently, for every individual state within the computational basis, the Pauli-X gate functions equivalently to a classical NOT gate [see (7)]

$$|0\rangle \xleftrightarrow{G_X} |1\rangle. \tag{7}$$

2) Pauli-Z: Similar to the Pauli-X gate, the Pauli-Z gate corresponds to a π-radian rotation of the input qubit's state around the Z axis on the Bloch sphere. Consequently, when this gate is applied to a qubit's state, it results in the interchange of their amplitudes relative to the Hadamard basis [see (8)]

$$\alpha\,|+\rangle + \beta\,|-\rangle \xrightarrow{G_Z} \beta\,|+\rangle + \alpha\,|-\rangle\,. \tag{8}$$

Thus, the Pauli-Z gate also acts as a classical inverter gate for each of the two states of the Hadamard basis [see (9)]

$$|+\rangle \xleftrightarrow{G_Z} |-\rangle. \tag{9}$$

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3) Hadamard (H): One of the most widely used quantum gates is the Hadamard gate, mainly due to its ability to allow going from a basis state to a superposition one. Consequently, it can be employed to convert a qubit from the computational basis to its analogous representation in the Hadamard basis [see (10)]. This gate symbolizes a π-radian rotation around the X+Z diagonal axis of the Bloch sphere

$$|0\rangle \overset{G_H}{\longleftrightarrow} |+\rangle$$
$$|1\rangle \overset{G_H}{\longleftrightarrow} |-\rangle. \tag{10}$$

4) SWAP: This gate affects the states of two input qubits, interchanging their values [see (11)]

$$|\psi_a\rangle|\psi_b\rangle \overset{G_{SWAP}}{\longleftrightarrow} |\psi_b\rangle|\psi_a\rangle. \tag{11}$$

E. Projection

In the majority of quantum algorithms, qubits undergo a series of quantum gates until reaching a point where observing the outcome becomes interesting. However, directly determining the quantum state is not feasible. Instead, when measuring a qubit, a projection of its state vector along a specified axis is obtained. Specifically, causing the collapse of a qubit's state is equivalent to randomly projecting it onto one of the axes of the Bloch sphere. A qubits in a state aligned with a particular axis, when projected onto the corresponding basis, is always measured with a probability of 1 for the real value of the state. However, when measured along an axis where the state is in an equiprobable superposition, it is expected that half of the time it will be projected in one direction and half in the opposite direction. For instance, when projecting onto the Z axis, either of the states $|+\rangle$ or $|-\rangle$ will become one of the two states $|0\rangle$ and $|1\rangle$ with a probability of (1/2). The same principle applies to an arbitrary state $|?\rangle$ that is in a superposition state relative to that basis

$$\left.\begin{matrix}|+\rangle\\|-\rangle\\|?\rangle\end{matrix}\right\} \xrightarrow{P_Z} \left\{\begin{matrix}|0\rangle\\|1\rangle\end{matrix}\right.. \tag{12}$$

A scenario similar to the one described above arises when performing a projection along the X axis

$$\left.\begin{matrix}|0\rangle\\|1\rangle\\|?\rangle\end{matrix}\right\} \xrightarrow{P_X} \left\{\begin{matrix}|+\rangle\\|-\rangle\end{matrix}\right.. \tag{13}$$

F. Entanglement

In quantum computing, the word entanglement refers to a connection between the uncertain states of two or more qubits. This phenomenon lacks a classical equivalent, making it challenging to conceptualize. To aid in visualization, one can imagine the existence of two entangled coins, where simultaneously flipping both coins will consistently yield identical outcomes. Importantly, this effect remains unaffected by the distance between the coins. It is crucial to emphasize that there is no form of communication between the entangled entities. Instead, the identical measurement results of two entangled qubits a and b stem directly from their shared global state, as defined in

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0_a0_b\rangle + |1_a1_b\rangle). \tag{14}$$

Hence, when measuring two entangled qubits in a basis where their states are in superposition, they remain collectively uncertain. There is a 50% probability of obtaining either of the two possible values, even though, in accordance with (14), a measurement will always yield the same value with a 100% probability.

G. Decoherence

The phenomenon in which quantum systems lose their distinctive features, and make the transition to classical systems on their own is known as quantum decoherence. In quantum experiments, this occurrence is quite common, so many efforts are made to minimize the system's dependence on the environment. There is also a need for precise control over the system to achieve computational objectives, including initializing the system to a known state, executing well-defined transformations, etc. Consequently, reducing decoherence becomes a significant area of research in hardware implementations of quantum processors, aiming to maintain absolute control over the system.

IV. Qubit—The Game

A. Overall Description

1) Purpose of the Game: "Qubit: The Game" is a card game in which the player's goal is to be the first player to form a binary key, referred to as the password, randomly selected before playing. To achieve it, the players have to compete to strategically lay down on the table a combination of qubit cards that form the objective password sequence. Equation (15) shows the language containing all possible sequences of cards played on the board that win the game, with key $\in (0|1)^*$ being the target binary chain

$$L = \{w : (0|1| + |-)^* \text{ key } (0|1| + |-)^*\}. \tag{15}$$

The game should be played by two to six players, with four being the ideal number for a standard game. The duration of each game will depend on the players' experience with the game. Thus, the first games can be a little slower, so that they will lighten up as more knowledge is acquired about the rules and mechanics of the game. Up to four players, it is recommended to set the target password size to 3 or 4, depending on whether you want a short game (10–20 min) or a medium game (15–30 min). For games with five players or more, an objective password of length 3 is recommended, to achieve intermediate or even long games (+30 min). The essential components required for gameplay include the "Qubit: The Game" card deck, a six-sided die and a coin.

2) Actions: There exist two potential kinds of action: 1) draw a card from the draw piles and 2) use a card from your hand by playing it.

It is essential to carry out every action individually, fully completing each action to be performed before beginning the next. This is important as the order in which actions are performed greatly affects how the game unfolds. More details about the actions can be found in Section IV-C.

3) Turns: The starting player is chosen at random after choosing the target password. In the first round, every player performs three actions on their turn. Each time a player ends their turn, it passes to the next player in clockwise order. This dynamic is repeated until a full round is completed, having all the players already played their first three actions. From that moment, the players must roll a die to know how many actions they must perform per turn, according to the following guidelines: values 1, 2, and 3 grant one action; 4 and 5 provide two actions; and 6 confers three actions. This rule balances the outcome of the roll, reducing the duration of the turns and favoring more dynamic games.

B. Design

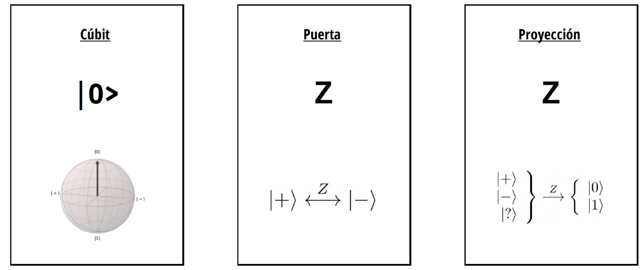
The decisions for designing the game as a team board game with strategies based on scientific concepts were based on the following three reasons. First, the goal was to encourage cognitive engagement by actively involving students in strategic thinking, problem-solving and decision-making within the context of the proposed game's mechanics. This interactive nature of the game stimulates critical thinking skills, enhances analytical abilities and fosters a deeper understanding of the subject matter. Second, the affective aspect of learning is nurtured through face-to-face interaction. As students play the game together, they experience a range of emotions, such as excitement, competition, collaboration, and even moments of challenge or success. This emotional engagement enhances motivation, promotes a positive attitude toward learning, and creates a memorable and enjoyable learning experience. Finally, the social dimension of learning is amplified as students collaborate, communicate and negotiate with one another during the game. They develop teamwork and communication skills, learn from each other's perspectives, and build social connections. This collaborative environment fosters a supportive and inclusive learning community, where students can exchange ideas, discuss concepts, and learn from different approaches and viewpoints. In summary, a board game that requires face-to-face interaction within groups of students serves as a powerful tool to integrate cognitive, affective, and social aspects into the learning process. It cultivates critical thinking, emotional engagement and collaborative skills, ultimately enhancing the overall learning experience.

The arrangement of the playing area consists of the individual players' hand cards, a tabletop section for each player to place their played cards, three draw piles, and four resource piles.

Each player's hand comprises the cards they have drawn and are yet to be used (see Fig. 2). The played qubit cards remain on the player's side of the table, with the goal of obtaining the target password before their opponents.

The three draw piles are described below.

1) *Qubit:* This pile is composed of qubits in an undefined state ($|?\rangle$), which should be interpreted as a qubit in a state on the Y axis ($|?\rangle \in \{|+i\rangle, |-i\rangle\}$). Therefore, when projecting one of these on either axis (X or Z), the probability is equal for the two possible values. For the simplicity of the game, the application of gates on these qubits is not allowed.
2) *Gate:* Within this pile are the quantum gates which refer to the transformations that can be applied on the qubits. The following gates are available in the game: X, Z, H, and *SWAP* [see (7) and (9)–(11)].
3) *Projection:* Within this pile are the cards that allow a qubit to be projected onto a fixed axis. There are two kinds of projections.
   a) *In Relation to the Z Axis:* To apply this card to a qubit that is not currently on this axis, a coin is tossed and, depending on the result, the qubit becomes $|0\rangle$ or $|1\rangle$. In particular, heads indicates the conversion to the value $|0\rangle$ and tails to the value $|1\rangle$ [see (12)].
   b) *In Relation to the X Axis:* The same principle applies to this other axis, where heads indicates the value $|+\rangle$ and tails $|-\rangle$ [see (13)].



(a) (b) (c)

Fig. 2. Example cards from each of the draw piles. (a) Qubit. (b) Gate. (c) Projection.

Within any of these piles, there exists a special type of cards, known as *event cards*. These events are a key component of the game, as they make the game flow more unpredictable and they do not always benefit the player that activates them, adding a strategic incentive to the game. To play an event card, simply follow the instructions given in the card description. Some of these cards have a lightning bolt mark, indicating that they are *instant cards* that must be played immediately, without those actions affecting the number of actions the player is due on their turn as indicated by the die. Other noninstantaneous event cards may be kept in the player's hand for later use. Some of these cards may be even played during another player's turn, as per its usage description.

Within each resource pile there are 16 cards for each value ($|0\rangle$, $|1\rangle$, $|+\rangle$, or $|-\rangle$). They cannot be drawn arbitrarily. To take one of them, another card must indicate so. For example, an instant event card may indicate that a $|0\rangle$ should be drawn into the player's hand. Another example is that by applying an X gate to a $|0\rangle$ qubit, both cards are discarded and replaced by a $|1\rangle$ card in their place.

C. Game Dynamics

At first glance, it may appear that the optimal strategy for attaining victory in the game is for the player to simply use

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their cards in their favor to achieve victory. However, this is usually not the only nor the best path. Gates, projections, and events may be applied to any of the played qubits on the table, even those that are not owned by the active player. A card that can be useless applied to a player's cards can significantly slow down their opponent's progress in the game. This aspect of the game allows for competition and coalition mechanics to organically arise.

In this game, the order in which the cards are played is very important. When playing a qubit, it is left on the player's side of the table; placing it, as desired, as far to the right or to the left as possible with respect to the qubits already played. Once a qubit card is placed on the table, the player may not change its location, unless an event card indicates so. In this way, if the projection of a qubit leaves it in an undesired state, it must be corrected using gates and/or projections. Special emphasis is placed on the fact that the application of gates and projections are not commutative operations. Projecting first and then applying a gate may not be the same as first applying the same gate and then the same projection, since projecting involves changing what is being observed.

An event card exists that enables the indefinite entanglement of two played qubits. Once interleaved, when either is projected onto either axis, they are both set to the same result value. Furthermore, it is possible to entangle more than two qubits with each other, entangling a new one with others that were already entangled.

It is important to mention that events are permanently discarded once played, unlike the rest of the cards that can appear more than once. In this way, an analogy with decoherence is made, since there are fewer and fewer events, it is as if the state of the game tends to be more and more classic. As time passes, fewer events occur, fewer surprises, less randomness, and the game becomes less quantum. This also serves as a balancing mechanic if the game lasts too long, since without events it becomes a much more strategic and predictable game.

D. Quick Start

The following is a detailed description of an example of game development. A video simulation of this game can be found at [34]. To keep the example game short, the key length is set to 2. Subsequently, an arbitrary random string of this length is chosen to be considered as the target password, presumed to be "10." Assume two players: 1) Alice and 2) Bob. Both, on the first turn, have three actions.

1) Alice starts by performing her first action so she draws a card from the qubit pile, expecting to get a qubit in the $|?\rangle$ state. Instead, she is surprised with an instant event card, which states that all players must discard one of their played qubits. As no qubits have been played, the event is simply discarded. Alice attempts to draw a qubit once again, but she ends up with an instant event card that rewards her with a qubit in $|1\rangle$ state. For her last action, she reveals the $|1\rangle$ qubit and places it in her side of the table.
2) Bob also starts his turn drawing from the qubit pile. He draws an instant event card that forces him to draw the next two cards from the qubit pile, giving him two $|?\rangle$ qubits. Next, he draws from the projection pile, obtaining an X-axis projection. Finally, he draws an instant event card from the gate pile, which forces two played qubits to be swapped. As there is currently only one played qubit (Alice's qubit), the event is simply discarded.
3) The first round is now completed. From this moment on, the players must roll the die to determine how many actions they must perform during their turn. It is Alice's turn, so she rolls the die and gets a 6, meaning that she must perform three actions during this turn. She draws a card from the qubit pile, getting a qubit in the $|?\rangle$ state, which she immediately places to the right of her already played $|1\rangle$ qubit for her second action. As she now only needs to transform the $|?\rangle$ qubit into a $|0\rangle$ state to win, she draws from the projection pile, obtaining an X-axis projection.
4) Bob rolls the die, obtaining a 3, worth a single action. He decides to place a $|?\rangle$ qubit from his hand on the side of the table that is still empty, ending his turn.
5) Alice rolls a 4, which is worth two actions. She decides to project her undefined qubit in the X-axis, playing the projection card she drew earlier. She tosses a coin and gets tails, equivalent to a qubit in a $|-\rangle$ state, so she replaces her $|?\rangle$ qubit with one of the $|-\rangle$ cards available in the resource pile. For her last action, she draws from the gate pile and gets an entanglement event that may be played as any other gate card, entangling two undefined qubits together.
6) Bob rolls a 6, granting him three actions. He places his other $|?\rangle$ qubit on the table and projects his leftmost qubit in the X-axis. He flips the coin, and he also gets tails, replacing this undefined qubit with a qubit in the $|-\rangle$ state. Finally, he draws a Hadamard gate from the gate pile.
7) Alice rolls a 6 once more, awarding her three actions. She draws from the gate pile, obtaining a SWAP gate, which would allow her to swap any two played qubits. She decides to play this card, swapping her $|-\rangle$ qubit with Bob's $|?\rangle$ qubit, as she believes that it is easier to work with an undefined qubit and that this play will make it harder for Bob to win. She ends her turn by using the projection pile, drawing an instant event card that forces one of the player's $|?\rangle$ qubits to collapse on the X-axis. She chooses herself to be affected by the event and tosses a coin to determine the result of the projection. Thus, she gets heads, so she draws a qubit in the $|+\rangle$ state.
8) Now it is Bob's turn, so he rolls a 5, granting him two actions. He realizes that Alice may win soon if he does not tamper with her played qubits, but the only card he has in hand is a Hadamard gate, which he wants to use to get closer to the agreed objective password. He then uses the gate on his leftmost $|-\rangle$ qubit, changing its

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state to $|1\rangle$. For his last action, he draws another gate, obtaining a new Hadamard gate.

9) Alice rolls a 5, giving her a total of two actions to perform. She acknowledges that she may win by getting lucky using a Z-axis projection or by using one of the few Hadamard gates that are left in the gate pile. She decides to draw a gate card, obtaining the desired Hadamard gate. She uses it in her qubit in the $|+\rangle$ state, which transforms into the $|0\rangle$ state. After this play, Alice has placed in the table the objective password, 10, so Alice is declared the winner and the game ends.

In this small example, some of the basic mechanics of the game have been put to the test, showing how the randomness present in the game can quickly lead to victory, making the game very dynamic. All this without losing the high-strategic component, since knowing the possibilities of the results of randomness, it is up to the player whether to choose safer or riskier situations.

V. Pilot Experience With K-16 Students

A. Study Design

The research carried out on the impact of the proposed game was using a cohort of 96 students enrolled in the first year of Spanish Baccalaureate and 19 students enrolled in the first year of high school of a secondary school in Spain. The data collection process involved the administration of a questionnaire in several stages, which facilitated the collection of information for statistical analysis, allowing insights into the potential of the game. Since the population is composed of minors, the process followed in this study for data collection has been approved by the University ethics committee after sending them the participation forms. In addition, the informed consent of the involved students and their legal tutors have been managed through their teachers.

Several demographic data of the population involved in this study have been collected during this survey. Regarding their ages, 74.58% of the participating students are 16 years old, while 25.42% are 17 years old. Furthermore, 59.32% are females, 35.59% are males, and 5.09% preferred not to say so. Regarding their prior experience related to quantum computing, they were asked to rate it from 1 to 5 meaning from not at all to a lot. According to their responses, 85% had no experience at all, 10% rated it with a 2 and 5% with a 3. They were also asked at the beginning of the survey if they were interested in computer science using the same range. To this question, 11.67% answered that they were not interested, 11.67% with a 2, 41.67% with a 3, 21.67% with a 4, and 13.32% who were very interested. This study was carried out with students within the specific subject of Mathematics of the secondary studies of the following specialties: 58.33% of Natural Sciences, 31.67% of Technology, and 10% of Humanities and Social and Health Sciences.

Specifically, the employed methodology encompassed the following procedures. To assess the level of achievement of each student, a simple pretest was administered, measuring their attitude, interest and knowledge about the topic in question. Subsequently, the students attended a 30-min lecture on the fundamentals of quantum computing and the gaming experience, given by one of the authors of this article. Immediately after the talk, additional specific questions related explicitly to the game were raised. The students then participated in approximately 1 h of play, after which the comprehensive assessment was administered again. This approach allowed the use of test and retest reliability, since scores on both assessments could be correlated.

The survey covered the following ten specific questions.

Q1: Do you know anything about quantum computing?
Q2: Are you interested in quantum computing?
Q3: Does quantum computing seem easy to you?
Q4: In the future, would you like to work in an area close to quantum computing?
Q5: Does the game seem easy to you?
Q6: Do you find the game useful to understand quantum computing concepts?
Q7: Would you like to have the game?
Q8: Mark the three concepts that you find most interesting.
- ☐ Bloch sphere ☐ qubit.
- ☐ quantum gate ☐ projection.
- ☐ entanglement.

Q9: When applying an H gate card to a played card of qubit $|0\rangle$, what is left?
- ☐ $|0\rangle$ ☐ $|1\rangle$.
- ☐ $|+\rangle$ ☐ $|-\rangle$.

Q10: What do you get when applying a projection card on the Z axis on a played qubit card $|+\rangle$?
- ☐ The qubit card $|1\rangle$.
- ☐ One of the qubit cards $|0\rangle$ or $|+\rangle$, randomly on coin toss.
- ☐ One of the qubit cards $|0\rangle$ or $|1\rangle$, randomly on coin toss.
- ☐ The qubit chart $|+\rangle$, staying as it was.

Questions Q1 to Q7 requires a response consisting of a 5-point Likert scale, ranging from 1 (not at all) to 5 (extremely), whereas the remaining questions employed multiple-choice format (question Q8) and single-choice format (questions Q9 and Q10).

Each question was addressed twice by every student. Questions Q1 to Q4 were answered during the pretest prior to the lecture and at the end, after playing. Questions Q5 to Q10 were answered immediately after the lecture and at the end, after playing.

B. Results

In order to validate the fulfillment of the different objectives of the game, a statistical study was carried out based on 3 null hypotheses, through the responses to the 10-question survey carried out with the students. First, in relation to the improvement of motivation to learn quantum computing through the game, the first null hypothesis raised in the study of the data obtained from the first four survey questions is denoted as H1 below. Through questions Q5 to Q7, the second null hypothesis related to the game is called H2 below. Finally, the evaluation of the improvement in the comprehension of fundamental concepts of quantum computing with the use

TABLE I
STUDENT'S T-TEST ON QUESTION Q1

	Q1	Q1 retest
Mean	1,243478261	3,07826087
Variance	0,255987796	1,055225019
Observations	115	115
Pearson Correlation	0,131792736	
Hypothesized Mean Difference	0	
df	114	
t Stat	-18,15762907	
$P(T \leq t)$ one-tail	9,86763E-36	
t Critical one-tail	1,658329969	
$P(T \leq t)$ two-tail	1,97353E-35	
t Critical two-tail	1,980992298	

of questions Q9 and Q10, thereby allows testing the null hypothesis H3 below.

H1: There exists no significant difference in students' attitudes toward quantum computing pre and post exposure to the game.

H2: There exists no significant difference in students' interest in playing the game pre and post exposure to it.

H3: There exists no significant difference in students' basic knowledge of quantum computing pre and post exposure to the game.

Paired two-sample Student's *t*-tests have been used in this research as all individuals answered the survey twice. Specifically, three hypotheses tests were conducted to examine if the means before and after the game were equivalent for each question, employing a significance level of 0.05. Consequently, when a *p*-value below 0.05 is obtained, the result is considered statistically significant, resulting in the rejection of the corresponding null hypothesis.

The initial analysis of students' responses to question Q1 reveals a noteworthy finding as the median response for this question before the game is 1 whereas after the game is 3. Table I provides the *t*-test results for the responses to question Q1, leading to the conclusion that there exists a significant difference in individuals' self-perception of their knowledge of quantum computing before and after the game.

A similar study of question Q2 results in a *p*-value of 2.45389E-07, further confirming a significant difference in responses regarding interest in quantum computing before and after the game. The findings indicate that individuals display greater interest in the subject after engaging in the game.

An analysis of variance examining the perception of topic difficulty before and after gameplay, as indicated by question Q3, yields a *p*-value of 9.32517E-20. Hence, the results demonstrate a significant difference in students' perception before and after playing.

The obtained *p*-value for question Q4 is 0.001512692, implying that it is conclusive to establish a significant distinction in students' attitudes toward working in quantum computing.

As aforementioned, the outcomes of the *t*-tests conducted on questions Q1 to Q4 support the rejection of the null hypothesis H1, thus concluding that a significant difference exists in students' attitudes toward quantum computing before and after exposure to the game.

The two-sample Student's *t*-test results for question Q5 reveal a *p*-value of 5.33453E-25, so it follows that the game is perceived as easy.

The *t*-test analysis of question Q6 generates a *p*-value of 4.65075E-08, indicating that students perceive the game as useful for comprehending quantum computing concepts.

Finally, question Q7 yields a *p*-value of 5.40229E-21, suggesting that students express interest in having the game.

Thus, the results of questions Q5, Q6 and Q7 supported the rejection of the second null hypothesis H2, concluding that there exists a significant difference in students' interest in playing the game pre and post exposure to it. Verbatim comments from the students' responses further support this finding, such as "I really enjoy the game because it is entertaining and engaging" and "The game is awesome:-)."

Regarding question Q8, it is observed that after playing the game, the initial interest in qubit, quantum gate, and entanglement concepts is maintained, while less interest is shown in the concept of Bloch sphere. Another observation related to question Q8 is that, in general, participating students have greater interest in the concept of projection after playing the game than after the talk. This entails a very relevant change in perception because after the talk it is a concept that seems complicated and generates some rejection, but nevertheless, after playing they consider it useful and fun.

Finally, questions Q9 and Q10 confirm the game's efficacy in acquiring knowledge related to basic concepts of quantum computing. On the one hand, question Q9, regarding the Hadamard gate, the percentage of correct answers increased from 49.15% to 81.36% between before and after playing. On the other hand, similarly, question Q10 on projection received 33% correct answers before playing the game, which increased to 46% after playing. Therefore, based on both questions, it can be concluded that the null hypothesis H3 is rejected, since there is a significant difference in the basic knowledge of quantum computing of the students before and after the exposure to the game.

C. Discussion

This work aims to test the hypothesis that gamification-based methods used by teachers significantly contribute to increasing students' interest in learning complex topics such as quantum computing. A pilot study was carried out with a large group of high school students to test the potential of the proposed game. While most of the results obtained from the pilot study follow expectations, the analysis presented here provides statistical evidence of the game's potential. In particular, the study concluded that the use of the designed card game helps improve performance and encourages a positive attitude toward learning quantum computing. Thus, the proposed game can be seen as a useful tool to introduce quantum computing to nonspecialists.

During the study it was noted that there is some confusion regarding the coin toss mechanic, as it is not immediately obvious how "heads" or "tails" maps into the possible outcomes of a projection. On the other hand, the visual design of the game itself seems to also be a valuable aspect to consider. Feedback from the testers of the game seems to reflect that the use of color to aid the quick identification of cards may benefit the overall gameplay, as well as the organization of the various decks when preparing the game. Taking these observations into account, a visual redesign of the game will be considered for the development of future studies, with custom assets that may aid in clarifying mechanics and improving the overall perception of the game.

Besides, there are several possible lines of research that deserve further study, such as the analysis of the effects of the different event cards on the probability of winning the game. Likewise, the different alliance/competition strategies that players can develop could be studied from the point of view of game theory.

VI. Conclusion

This article has presented an innovative board game called "Qubit: The Game," which was designed with the main goal of fostering curiosity in quantum computing and improving understanding of various fundamental notions in the area, such as qubit, superposition, Bloch sphere, quantum gate, projection, entanglement, or decoherence. Specifically, the rationale, design and implementation of the proposed game have been defined in this document.

An initial research on the potential of the game was carried out with a group of high school students, and a statistical analysis of the students' responses to a survey was carried out according to a methodology that involved five phases: 1) pretest; 2) talk; 3) test; 4) play session; and 5) post-test. This study made it possible to statistically determine the fulfillment of the game objectives, defined through three null hypotheses to verify the promotion of motivation to learn the topic, the interest in the game, and the understanding of essential concepts of quantum computing, respectively. Thus, it has been possible to conclude that this game has the potential to be an effective tool to teach basic quantum computing to nonspecialists.

Therefore, two modifications are proposed: the first one is an extension using the Y-axis, which implies the addition of new cards (such as qubit states $|+i\rangle$, $|-i\rangle$, or y projection). The second one is a variation in the mechanics of the game, involving a change in the objective by considering the cryptographic point of view, and applying different QKD algorithms (such as BB84, E91, or B92 [35]). In fact, both options can be considered through the implementation of the Six-State protocol [36]. These additions could be implemented with optional specific expansion card sets. Therefore, these modifications would not affect the learning curve of the game as explained in this article, but would create new learning challenges and strategies for players who wish to further expand their knowledge of quantum computing.

However, there are still numerous open lines related to the game. First of all, future studies will seek a more diverse set of participants and questions [37]. In particular, the plan is to analyze the usefulness of the game with low ages, and especially to test if its use might be effective in attracting female students to STEAM subjects [38]. Furthermore, there is an intention to release the game as an open source initiative, in order to allow educators, students, and card game fans to use it freely.

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