Qubit: The Game. Teaching Quantum Computing through a Game-Based Approach

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Abstract. Quantum computing is a promising and rapidly growing interdisciplinary field that attracts researchers from science and engineering. Based on the hypothesis that traditional teaching is insufficient to prepare people for their introduction to this field, this paper presents *Qubit: The Game*, an innovative board game to promote both the motivation to learn quantum computing and the understanding of several essential concepts of that field. The reasons for the choice of game type, design and mechanics, and the followed methodology are described in detail here. This paper also includes a preliminary study to determine the effect of the proposed game on the perception, interest and basic knowledge of quantum computing in a group of high school students. The study findings reveal that the designed game is a powerful tool to foster interest and teach essential concepts of a subject as difficult as quantum computing, which can be of great help in introducing more complex concepts.

Keywords: Quantum Computing · Education · Game-Based Learning.

1 Introduction

Quantum computing is an exciting discipline that will become increasingly relevant due to its potential applicability in many areas. One of those areas is cybersecurity, which must be reconstructed in the face of the threat posed by the possible availability of quantum computers that make it possible to break the cryptographic algorithms on which the main current secure communication technologies are based. However, quantum computing is also a conceptually challenging discipline, as for most people, everything related to quantum concepts is perceived as an abstract and challenging field that involves difficult mathematical formalisms and is incompatible with a conception based on the classical model. This work aims to help people adapt to a world where quantum computing will be essential.

Research in didactics of mathematics and physics shows that the majority of students present difficulties in the acquisition of complex concepts such as those related to quantum mechanics. In fact, numerous studies conclude that students

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need to feel engaged and interested in the subject for learning to take place [1]. In addition, it is also known that for learning to be meaningful and authentic, it must be built piece by piece, since learning occurs as the student processes and interprets the meaning of each new information they receive. For this reason, games to teach science have been used for more than a century in order to take advantage of the opportunity they offer to integrate cognitive, affective and social aspects with learning [2]. In fact, the main conclusions of some studies carried out on learning based on games, in comparison with the one based on traditional methods, can be summarized as follows: it promotes greater student interest, it can consume more time, and it can result in a greater understanding of a concept and greater retention.

This work proposes *Qubit: The Game*, an innovative game as a way to introduce, in an entertaining way, essential concepts related to quantum states and transitions between states. It is a game that can be played by two or more players, and that is based on three types of cards: qubit, quantum gate and projection, with completely new mechanics. The object of the game is to obtain a binary sequence that is chosen at the beginning as the target key.

A preliminary study on the effect of the proposed game was carried out with secondary school students, and the conclusions were promising. That study is part of a more comprehensive analysis that is being done with larger groups of players and broader surveys to look at different results that could perhaps lead to improvements to the game.

This paper is organized as follows. In Section 2 some related works are mentioned. Section 3 introduces the quantum computing concepts covered in the proposed game. Section 4 is devoted entirely to a detailed description of the proposed game, including design, mechanics and quick start. Section 5 describes the pilot experience on the game that was carried out with a group of students, highlighting some findings of the study and a brief discussion. Finally, Section 6 of Conclusions closes the paper.

2 Related Works

In the literature we can find different proposals to improve the teaching of quantum concepts, including tools based on interactive simulations and visualization and some quantum-based games, although in most cases, these game proposals are digital. In this work, however, the decision was made to design a board game that must be played in person, in groups, in order to favor the integration of cognitive, affective and social aspects with learning. For the design of the cards, the authors drew on extensive experience with the IBM's Qiskit [3] tool, one of whose greatest strengths in visualization.

Among the efforts to improve the teaching of quantum computing, the publications [4], [5], [6] and [7] stand out. On the one hand, the work [4] gives an overview of online learning and teaching materials for a first course in university quantum mechanics, including research-based interactive simulations. On the other hand, the paper [5] is a recent paper on the teaching of a graduate-level

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quantum computing course and quantum computing modules in high schools, which develops problems to be solved on IBM's quantum computing simulator. Besides, the report [6] describes an experience teaching an undergraduate course on quantum computing using a practical, software-driven programming-oriented approach. Finally, the work [7] proposes an approach for secondary school students, including instructional materials to enhance the educational and cultural potential of quantum computing. Unlike those four works, the research presented in this paper is not focused on the design of modules for curricular or extracurricular courses, but on an educational proposal based on a game that can be used in any of these courses, or as a simple leisure activity.

Various proposals for tools supported by interactive simulations and visualization to teach quantum mechanics can be found in the bibliography [8–11]. First, the work [8] explores how interactive animations and simulations can enhance student understanding of quantum mechanics and quantum information theory. In the remaining papers, several specific tools are proposed for quantum visualization, including PhET [9], QuILT [10] and QuVIS. Note that the objective of this work is different from the one of the last five works mentioned because the focus is not on teaching quantum mechanics through interactive simulations or visualization tools, but rather on introducing essential concepts of quantum computing through a board game.

Among the closest bibliographical references to this work, two games proposed to teach quantum computing stand out: Quantum Odyssey [12] and Entanglion [13]. On the one hand, Odyssey is a software-assisted visual game for learning how to create new quantum algorithms and optimize them for quantum computers. On the other hand, Entanglion is a board game whose main objective is to introduce the fundamental concepts of quantum computing. *Qubit: The Game* is a card game, with an introductory focus for all types of audiences. In fact, the objective is not only educational but also to promote attraction towards the subject, and both objectives can be considered fulfilled according to the feedback received from the study carried out with young people.

3 Quantum Concepts

3.1 Qubit

Traditionally in computing, the smallest unit of information is called a bit. At any time, a bit can be in only one of two possible states, normally represented as 0 and 1. On the contrary, in quantum computing the basic unit of information is the quantum bit or qubit, which can be found in one of the infinite possible combinations of 0 and 1, in what is known as a superposition state [14]. This concept is normally represented with respect to the computational basis ($\{|0\rangle, |1\rangle\}$) by Eq. 1, with complex coefficients ($\alpha, \beta \in \mathbb{C}$), whose sum of the squares of their norms is equal to one ($||\alpha||^2 + ||\beta||^2 = 1$).

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

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Thus, the state $|0\rangle$ is the one whose $\alpha = 1$ and whose $\beta = 0$. The opposite case occurs for the $|1\rangle$ state.

3.2 Superposition

A state in superposition is one that cannot be represented by a single component with respect to a basis. Two superposition states with respect to the computational basis are illustrated in Eq. 2, 3.

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

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

In the two cases shown in Eq. 2, 3, the states lie in an equiprobable superposition of the states $|0\rangle$ and $|1\rangle$, given that $||\alpha||^2 = ||\beta||^2 = \frac{1}{2}$.
However, the superposition with respect to one basis can be seen as a basic state on another basis. For example, an alternative way of defining qubits is with respect to the Hadamard basis, formed by the states $|+\rangle$ and $|-\rangle$. In this case, these vectors that make up the basis are in basic states, and the rest are in a superposition state. For example, with respect to the Hadamard basis, the states $|0\rangle$ and $|1\rangle$ are in an equiprobable superposition as illustrated in Eq. 4, 5.

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

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

3.3 Bloch Sphere

To better visualize the concept of superposition, the intuitive visual representation of the qubit, called the Bloch sphere, can be used. It is important to note that with this object, the goal is to represent two complex numbers (each represented by two real numbers) in three-dimensional space. This leaves one dimension missing, which is achieved by considering two opposite states on the sphere as orthogonal states (see Fig. 1).
Thus, to represent the state of a qubit, a sphere and an arrow inside it pointing to a point on its surface are needed. The higher the sphere points, the more likely it is to measure the $|0\rangle$ state; and the further down, the more likely to get the $|1\rangle$ state. The same is true for left and right, and the states $|+\rangle$ and $|-\rangle$, respectively.

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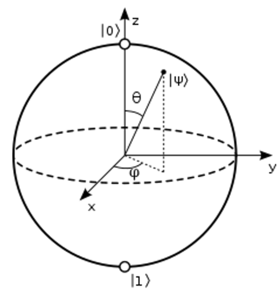

Fig. 1. Bloch Sphere

3.4 Quantum Gates

A quantum logic gate is a transformation that can be applied on the states of a small number of qubits. In the case of gates applied to a single qubit, they can be visualized as rotations in the state arrow of the qubit on the Bloch sphere. The gates that are dealt with in the proposed game are the Pauli gates X and Z, the Hadamard gate H, and the $SWAP$ gate.

Pauli-X This gate applies to a single qubit and can be represented as a rotation of π radians about the X axis on the Bloch sphere. This is due to the fact that the amplitudes of the qubit state are exchanged with respect to the computational base (see Eq. 6).

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

In this way, for each one of the two states of the computational basis, the Pauli-X gate acts as a classical NOT gate (see Eq. 7).

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

Pauli-Z Analogous to the Pauli-X gate, the Pauli-Z gate represents a rotation of π radians to the state of the input qubit about the Z axis on the Bloch sphere. Thus, this gate applied to the state of a qubit performs the exchange of their amplitudes with respect to the Hadamard basis (see Eq. 8).

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

Therefore, the Pauli-Z gate also acts as a classical NOT gate for each of the two states of the Hadamard basis (see Eq. 9).

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

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Hadamard (H) The Hadamard gate is one of the most used quantum gates, since it allows to go from a basic state to a superposition state. Thus, it can be used to transform a qubit in the computational basis and get its analog in the Hadamard basis (see Eq. 10). This gate represents a rotation of π radians around the diagonal X+Z axis of the Bloch sphere.

$$\begin{aligned} |0\rangle &\xleftrightarrow{G_H} |+\rangle \\ |1\rangle &\xleftrightarrow{G_H} |-\rangle \end{aligned} \tag{10}$$

SWAP This gate is applied to the states of two input qubits, swapping their values (see Eq. 11).

$$|\psi_a\rangle|\psi_b\rangle \xleftrightarrow{G_{SWAP}} |\psi_b\rangle|\psi_a\rangle \tag{11}$$

3.5 Projection

In most quantum algorithms, qubits go through numerous quantum gates until a point is reached where it is interesting to observe the result. However, it is not possible to determine the quantum state directly. Instead, when measuring a qubit, a projection of its state vector along a given axis is obtained. Specifically, forcing the state of a qubit to collapse is equivalent to randomly projecting it onto one of the axes of the Bloch sphere. The states of qubits that are already on an axis, when projected on the corresponding basis, are measured with probability 1 in the real value of the state. However, when measured on an axis with respect to which the state is in a state of equiprobable superposition, it is expected that half of the time it is projected in one direction and half in the opposite direction. In this way, for example, when projecting onto the Z axis any of the states $|+\rangle$ or $|-\rangle$ becomes one of the two states $|0\rangle$ and $|1\rangle$ with probability 0.5. The same would happen to an arbitrary state $|?\rangle$ that was in a superposition state with respect to that base (see Eq. 12).

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

A situation analogous to the one explained above occurs with the projection on the X axis (see Eq. 13).

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

3.6 Entanglement

Entanglement in quantum computing represents a correlation between the indeterminate states of two or more qubits. This effect has no classical analogue, so

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it can be hard to imagine. To try to visualize it, the existence of two entangled coins can be imagine so that tossing both coins at the same time will always yield exactly the same result. This effect does not depend on the distance between the coins. It is important to emphasize that there is no communication of any kind between the entangled objects. On the contrary, the result of the identical measurement of two entangled qubits a and b is a direct consequence of the fact that both share the same global state defined in Eq. 14.

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0_a 0_b\rangle + |1_a 1_b\rangle) \tag{14}$$

Therefore, two entangled qubits that are measured with respect to a basis in which their states are in superposition remain jointly indeterminate, since it is possible to obtain any of the two possible values with a 50% probability, although when performing the measurement (if the entanglement follows Eq. 14) the same value is obtained with a 100% probability.

3.7 Decoherence

Quantum decoherence is the process by which quantum systems lose the properties that characterize them, collapsing by themselves to a classical system. In quantum experiments, this happens quite often, so normally quantum systems are made as independent of the environment as possible. However, on the other hand, absolute control of the system is desirable to fulfill the computational objective, which implies the need to initialize the system to a known state, manipulate the system through well-defined transformations, etc. That is why decoherence reduction is a broad field of study in hardware implementations of quantum processors.

4 *Qubit: The Game*

4.1 General Description

Objective of the game. *Qubit: The Game* is a card game whose objective is to be the first player to form a binary key. This chain is randomly selected at the beginning of the game. The objective of the game includes the case in which said chain is a subsequence of the chain formed with all the cards on the player's board. Eq. 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 is designed to be played between two and six players, with four being the ideal number for a standard game. The duration of the games will depend on the experience of the players with the game, since the first games can be a little slower, so that they will lighten up as more knowledge is gained about the

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rules and mechanics of the game. Up to four players, it is recommended to set the target chain size to 3 or 4, depending on whether you want a short game (10-20 minutes) or a medium game (15-30 minutes). For games with five players or more, an objective key of length 3 is recommended, to achieve intermediate or even long games (+ 30 minutes).

Actions. There are 2 types of possible actions:

- Draw a card from the draw piles.
- Play a card that is in your hand.

It is important to perform each action individually, fully completing one action 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 4.3.

Turns. After choosing the target key, the starting player is randomly chosen. In the first round, each player performs three actions on their turn. Each time a player ends their turn, the turn passes to the next player in clockwise order. This dynamic is repeated until a round is completed, where all the players have already played their first turn of three actions. From this moment, the players must roll a dice to know how many actions they must perform per turn. The result of the dice defines how many actions must be performed as follows. Values one, two, and three grant 1 action; four and five provide 2 actions; and six sets 3 actions. In this way the probabilities are balanced, reducing the duration of the turns and favoring more dynamic games.

4.2 Design

The layout of the playing area is made up of each player's hand cards, a tabletop section for each player to place their played cards, three draw piles, and four resource piles.
Each player's hand is made up of the cards that are currently playable. Some of the played cards remain on the player's side of the table where the goal of obtaining the key is attempted before the opponents.
The three draw piles are described below:

- Qubit: Drawing from this pile is expected to obtain a qubit 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.
- Gate: In this pile are the letters referring to the operations to be applied on the qubits. The following types can be expected: X, Z, H and $SWAP$ (see Eq. 7, 9, 10 and 11).

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- Projection: In this pile are the cards that allow a qubit to be projected against a fixed axis. There are two kinds of projections:
  1. With respect 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 Eq. 12).
  2. Regarding the X axis: The same applies for this other axis, where heads indicates the value $|+\rangle$ and tails $|-\rangle$ (see Eq. 13).

In any of these piles, a special type of cards, called event cards, surprise the player. To play an event card, simply follow the instructions given in the text. In addition, some of these cards have a lightning bolt mark indicating that they are "instant" cards that must be played immediately, without counting actions consumed for that player's turn.

In each resource pile there are 16 cards of each value ($|0\rangle$, $|1\rangle$, $|+\rangle$, or $|-\rangle$). They cannot be stolen arbitrarily. To take them, another card must indicate it. For example, an event card may indicate that a $|0\rangle$ should be put into the player's hand; or by applying an X gate to a $|0\rangle$ qubit, discard both cards and put a $|1\rangle$ card in their place; etc.

4.3 Mechanics

It might seem that the most effective way to achieve the objective of the game is for the player to use their cards in their favor to achieve victory. However, this is usually not the only or the best path. Gates, projections, and events can be applied to the played qubits of the player playing them, or to the played qubits of their opponents. A card that can be useless applied to a player's cards can significantly slow down their opponent's progress in the game. That is why fun competition and coalition mechanics can be generated.

The order in which the cards are played is also extremely important. When playing a qubit, it is placed on the player's side of the table; placing, as desired, as far to the right or left as possible with respect to the qubits already played. Once a qubit card is placed on the table, it cannot change its position (unless an event card indicates so). In this way, if when projecting a qubit the desired value is not obtained, 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 applying the same gate and then the same projection, since projecting involves changing what is being observed.

There is an event card with which it is possible to entangle two indefinitely played qubits. Once interleaved, when either of the two is projected about any axis, both are defined with the same result value. Furthermore, it is possible to entangle more than two qubits among themselves, entangling a new one with others that were already entangled.

It should be noted that events are definitively discarded once they are played, unlike the rest of the cards that can appear more than once. In this way, an

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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 balances the game if the game lasts too long, since without events it becomes a much more strategic game.

4.4 Quick Start

The following is a detailed description of an example of game development. 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 key, presumed to be "10". Assume two players: Alice and Bob. Both, on the first turn, have 3 actions.

1. Alice starts by performing her first action: draw a card from the qubit pile, and get the expected qubit card in $|?\rangle$ state. In her second action, she decides to draw a gate card. In this case, she is surprised by an event card, which tells her that she has two additional actions. She draws a card from this pile again and gets a Hadamard gate. Next, she decides to draw a card from the projection pile, getting one on the Z-axis. She has one action left, in which she decides to play her qubit card by placing it on her side of the table. Now Alice's turn is up, so it is Bob's turn.
2. Bob decides to draw a qubit card, obtaining an event that forces him to pick a qubit in $|0\rangle$ state. Note that this card stays in Bob's hand, if he wished to play it he would have to consume another action. However, he prefers to draw another card from the same pile, and unluckily another event occurs that consumes the rest of the remaining actions in that turn.
3. Now that both players have played a full turn, at the beginning of each turn the dice must be rolled to decide the number of actions per turn to be performed. Alice rolls the dice and gets a 3, so she has an action that she spends taking a qubit card. She gets another qubit in $|?\rangle$ state.
4. Bob rolls the dice and gets a 6, so he has 3 actions. He uses the first one to draw a gate card and gets a quantum entanglement card. Now he draws another card from the qubit pile, getting a qubit in $|?\rangle$ state. Finally he places his qubit in state $|0\rangle$ on his side of the table.
5. Alice rolls the dice again and gets a 4, so she gets 2 actions. She uses both to place her two qubits in state $|?\rangle$ on her side of the table.
6. Bob rolls and gets a 5, so he gets 2 actions. The first of them is to place his qubit in state $|?\rangle$ to the left of the qubit already played in state $|0\rangle$. The last action is used in a move that can be considered a really good one: applying the entanglement card to the two undefined qubits of Alice. This way, when she measures one of them, the other one will collapse to exactly the same state and this can be a problem since the key is "10".
7. However, what could be a very good move will give the victory this turn to Alice. She rolls the dice and gets a 6, getting 3 actions. The first of these she consumes by drawing a gate card, with such good luck that she gets the

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X gate. At this point, she already knows she will win the game. Alice then applies projection card Z to any of her qubits. To do so, she flips a coin: it comes up tails, so both qubits are defined in the $|1\rangle$ state. With her last action, she flips her second qubit, getting the winning key "10".

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 generate 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.

5 Pilot Study

5.1 Survey Design

A first study on the effect of the proposed game was carried out with a sample of 19 students from a group of 1st year of high school of a secondary school in Fuerteventura (Canary Islands, Spain), who came to the University of La Laguna to participate in this study. They were administered a survey in different phases, producing data that was collected for use in statistical tests to draw conclusions about the potential of the game. In particular, the methodology followed was as described below. In order to determine each student's level of achievement, the student was given a simple pre-test on attitude, interest, and knowledge about the topic in question. Then they were exposed to a half-hour talk on the basics of quantum computing and the game, given by one of the authors of this paper. New questions specifically about the game were administered right after the talk. Then, after playing the game for an hour or so, the entire test was administered to the same students so that both test and retest reliability can be used, since scores from both tests can be correlated.
The ten questions included in the survey were the following:

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 3 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?
- ☐ $|0\rangle$
- ☐ $|1\rangle$
- ☐ $|+\rangle$
- ☐ $|-\rangle$

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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

The first seven questions had to be answered with a 5-point Likert scale from 1 (not at all) to 5 (extremely), while the last ones were multiple choice (question Q8) and single (questions Q9 and Q10).
All questions were answered twice: the first four were answered in the pre-test before the talk and at the end after playing, while questions Q5 to Q10 were answered right after the talk and at the end after playing.

5.2 Findings

To verify the achievement of the objective of the game on the promotion of motivation to learn quantum computing, the first hypothesis raised in the study of the data obtained with the first four questions of the survey is:

1. There is no significant difference in students' attitudes toward quantum computing before and after exposure to the game.

With questions Q5 to Q7 of the survey, another specific hypothesis about the game is analyzed through this null hypothesis:

2. There is no significant difference in students' interest in playing the game before and after exposure to it.

Finally, the understanding of some essential concepts of quantum computing is checked with the last two questions, which allows testing the hypothesis:

3. There is no significant difference in students' basic knowledge of quantum computing before and after exposure to the game.

In this study, paired two-sample Student's t-tests have been used because a single sample of individuals answered the survey twice. In particular, null hypothesis tests that both means before and after the game are equal for each question are carried out with a significance level of 0.05. Therefore, whenever a p-value less than 0.05 is obtained, the result is considered statistically significant and the corresponding null hypothesis is rejected.
The first analysis of students' responses to question Q1 yields a first clear result as the median response for this question before the game is 1 while after the game is 3. Indeed, Table 1 shows the results of the t-test on the responses to this question Q1, and the conclusion is that there is a significant difference in the self-perception of individuals about their own knowledge of quantum computing before and after the game.
A similar analysis with question Q2 yields a p-value of 0,034935624, which also confirms that significant difference in responses related to interest in quantum

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Table 1. Student's t-test on question 1.

	Q1	Q1 retest
Mean	1,263157895	3,526315789
Variance	0,204678363	0,929824561
Pearson correlation coefficient	0,046917565	
df	18	
t stat	-9,433414271	
$P(T \leq t)$ one-tail	1,08727E-08	
t critical one-tail	1,734063607	
$P(T \leq t)$ two-tail	2,17455E-08	
t critical two-tail	2,10092204	

computing between pre and post game, showing that after the game the individuals are more interested in the subject than before.

The analysis of variance of the perception of the difficulty of the topic before and after playing, shown with question Q3, produces a p-value of 0,001386775. Thus, the result shows that there is a significant difference between that students' perception before and after playing.

Regarding question Q4, the obtained p-value is 0,124235321, so in the analysis of variance of interest in working in quantum computing, it is not possible to conclude a significant difference in the attitude of the students. This is the only question in which the conclusion of the t-test is not conclusive with respect to the rejection of the null hypothesis.

As mentioned above, the results of the t-tests applied to these questions Q1 to Q4 can be used to support the rejection of hypothesis 1, so it is concluded that there is a significant difference in students' attitudes toward quantum computing before and after exposure to the game.

With question Q5, the results of the two-sample Student's t-test include a p-value of 2,83965E-05, so the conclusion is that the game is perceived as easy.

The t-test analysis of question Q6 yields a p-value of 0,015972972, so students perceive the game as useful for understanding quantum computing concepts.

Finally, from question Q7 of the survey a p-value of 0,003947853 is obtained, so the students are interested in having the game.

Thus, the specific hypothesis 2 about the game is also rejected, concluding that the students are clearly interested in playing the game. In this sense, it is worth including here some verbatim comments included by the students in their responses, such as: "I really like the game because it is fun and interesting" and "The game is cool :-)".

In question Q8, it was observed that after the game the greatest interest shown before playing in the concepts of qubit, quantum gate and entanglement was maintained, compared to less interest in the concepts of Bloch sphere and projection.

Finally, questions Q9 and Q10, answered twice, after the talk and after playing, allow us to confirm the usefulness of the game for knowledge acquisition regarding essential concepts of quantum computing. On the one hand, in question Q9

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about the Hadamard gate, 26.3% of answers were incorrect before playing, while there was unanimity in the correct answer after playing. On the other hand, the question Q10 on projection received 31.6% incorrect answers before playing the game, and only 10% incorrect answers after the game. Therefore, from both questions it can be concluded that the hypothesis 3 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.

5.3 Discussion

In general, this research has had as a general objective to verify the hypothesis that the use by teachers of methods based on gamification contributes to a great extent to maintain and motivate students' interest in learning complex subjects in general. In fact, this preliminary study clearly confirms that the use of a card game environment with interaction between students leads to an improvement in performance and a positive attitude towards learning complex a priori subjects such as quantum computing, so the game can be considered a useful tool to teach quantum computing to non-specialists.

Although most of the findings obtained from this preliminary analysis correspond to what is indicated by intuition, it is reassuring to see statistical evidence that the game produces the expected effect. However, it is clear that a larger study with a greater variety of individuals, questions and aspects is needed. In particular, as this was the first public release of the game, the main interest was to get a quick, high-level first impression of the game. However, in subsequent experiments, the Game Experience Questionnaire [15] will be used. Besides, another pending task is the study of the effects of the different event cards on the probability of winning the game.

An additional aspect that is worth looking at in future studies and versions of the game is the minimum level or age at which the game could be introduced. In fact, it would be interesting to analyze whether introducing these concepts at an early age would foster an interest in science and computing. Another interesting fact is that it seems that the use of games could be effective in improving performance and attracting female students to science and engineering [16], therefore, as an extension of this work, a specific study will be carried out in this regard.

6 Conclusions

This work has presented *Qubit: The Game*, which is an innovative card game whose main objective is to promote interest in quantum computing as well as the understanding of several essential concepts of the field. The preliminary study carried out with a group of high school students has made it possible to determine statistically the achievement of the objectives of the game. However, there are still several open lines in this work. It is planned to release *Qubit: The Game* as an open source project so that it can be freely used by educators, students, and card game enthusiasts. Another potential future work is the implementation of a simulator with AI players to study possible improvements of the game.

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