Quantum Penny Flip: an open source serious game for quantum computing assessment

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Abstract

Quantum computing bases on the exploitation of quantum mechanics to create computation systems. It inherits its benefits from quantum mechanics, but also its difficulties: quantum mechanics are counter-intuitive and hard to learn or even accept, even for its iconic mentors. This makes teaching quantum computing very challenging.
Serious games are games with a serious purpose, such as learning, training or social awareness.
The present work describes the development of a serious game for the purpose of learning quantum computing concepts. It deals with qubits, qubit states, superposition and the flip and Hadamard gates.
The game was made freely available to play with few system requirements to get to a broad audience. Also, its source code was made publicly available to modify and redistribute with no strings attached.
The authors feel that the objectives of this work were met, but there is further work to be done regarding the evaluation and improvement of the game.

1. Introduction

Quantum computing bases on the exploitation of quantum mechanics to create computation systems. It inherits its benefits from quantum mechanics, but also its difficulties: quantum mechanics are counter-intuitive and hard to learn or even accept, even for its iconic mentors. This makes teaching quantum computing very challenging.
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2. Conceptual Framework

2.1. Quantum Computing

Classical computing is based on silicon-based integrated transistors, which were discovered back in 1947 [1]. Further evolution in technology was founded on integration of transistors on chips at very large scales [2], but the basic computing element (the bit, binary digit) remained unchanged. This progression is however reaching unavoidable barriers, as transistors are approaching atomic dimensions.
Quantum computing brings new possibilities to computation, as it introduces a new computing element (named qubit) taking advantage of quantum physics [3]. Quantum effects of superposition and entanglement enable an advantage for quantum algorithms over classical ones, for certain kinds of problems. Main applications include cryptography, database search and simulation of quantum systems [4].
Quantum algorithms are being developed earlier than actual quantum computers. Quantum algorithms are modeled as quantum circuits, consisting in a number of qubits going through an array of quantum gates. Quantum gates are equivalent to logical gates in classic

computing, but exhibit distinctive properties as reversibility.
The X gate is the equivalent of the NOT classical gate. It turns a |1> to a |0>, and vice versa. The Hadamard gate takes a qubit into or out of a superposition state, depending on its initial state.

2.2. Quantum Game Theory

Game theory is the study of decision making of competing agents in some conflict situation [5]. Quantum game theory is an extension of classical game theory, which extends the space of moves for players using the effects of superposition and entanglement [6]. The field was introduced by Meyer in 1999 in his work Quantum Strategies [7]. The author proposes a few games confronting a classical and a quantum player, every time ending with a quantum victory.
The first one of the games he presents is PQ Penny Flip, in which this work is based.

2.3. A Game Theory Kickstarter: PQ Penny Flip

A quantum player (Q) and a player restricted to classical moves (P) play a three-turn flip coin game: first the coin is placed, heads up, in a box. Then Q plays, followed by P, and then Q again. If the coin is still heading up after the three turns, Q wins. Else, P is the winner.
P is allowed to decide whether to flip the coin (classical NOT gate) or not. Q, on the other hand, can perform a quantum gate.
The game results in a certain win for Q. The game sequence is shown in Figure 1, with |0> standing for heads and |1> corresponding to tails. By applying a Hadamard gate in his two turns, Q secures that the final result will be |0>, no matter if P flips or not the coin in his turn. The game sequence is shown in figure 1.

$$
\begin{aligned}
|0\rangle \quad & \overset{\text{Q}}{\underset{H}{\longmapsto}} \quad \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \\
& \overset{\text{Picard}}{\underset{\sigma_x \text{ or } I_2}{\longmapsto}} \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \\
& \overset{\text{Q}}{\underset{H}{\longmapsto}} \quad |0\rangle
\end{aligned}
$$

Figure 1: PQ Penny Flip game sequence

2.4. Serious Games

A Serious Game (SG) is a game which primary purpose is not entertainment, but a "serious" purpose [8]. This broad concept comprises educational games, simulators, social awareness and any game which has a purpose other than mere fun [9]. Despite this fact, fun is really important in the success of the effectiveness of the experience of a SG, so fun is not to be disparaged [10].

2.5. Open Educational Resources

Open Educational Resources (OER) are teaching, learning, and research resources that reside in the public domain or have been released under an intellectual property license that permits their free use or re-purposing by others. Open educational resources include full courses, course materials, modules, textbooks, streaming videos, tests, software, and any other tools, materials, or techniques used to support access to knowledge [11]. Serious games with educational purposes can therefore be a part of the OER movement, given the appropriate conditions.

2.6. Teaching Quantum Computing

Learning quantum computing is challenging, due that its foundations rely on quantum physics, which effects are counter intuitive and non observable at a macroscopic level. Even the mentors in the field admit that they do not actually understand the theory behind it. Quoting Richard Feynman, "I think I can safely say that nobody understands quantum mechanics."

This work explores the possibilities of SG as educational tools for understanding quantum mechanics and computing basics. The SG developed allows the player to interact with quantum particles, introducing quantum gates and superposition principles.

3. Background

Several works attempt to use videogames as tools for quantum teaching. Quantum Tic-Tac-Toe [12] introduces quantum effects in a recreation of the classic Tic-Tac-Toe. Quantum Minigolf [13] is a version of minigolf where the ball shows quantum behavior. qCraft is a Minecraft Mod which adds quantum blocks as analogies to quantum particles. Particle in a Box [14] is a platformer which emphasizes in the differences between the macroscopic world, where Newton laws sustain, and the microscopic world, where quantum mechanics are unleashed (figure 2).

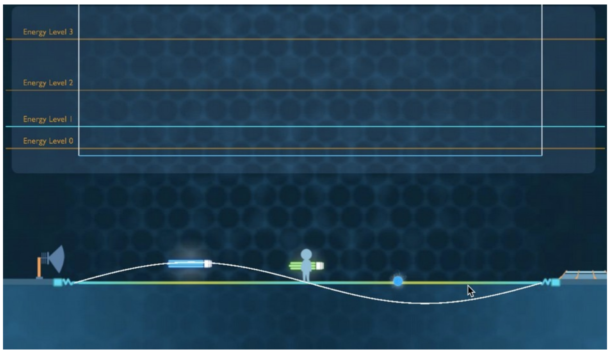

Figure 2: Shrinking to the quantum world in Particle in a Box

4. Methodology

QPF was developed following the methodology described in the Process Model for the Development of Serious Games (MPDSG) [15].
The MDPSG describes 3 groups of stakeholders involved in the development process: gaming experts, teaching experts and domain experts. Each of the groups provide requirements that must be attended and satisfied so that the resulting SG turns up to be an immersing experience, covering the pedagogical objectives in a realistic environment.
The process is by nature iterative, and in each iteration the contributions of each group are recorded in a descriptive document called the Game Design Document (GDD), which is a tool to communicate design aspects of the game among development teams specified in different disciplines [16].
Figure 3 shows the process as described in MPDSG.

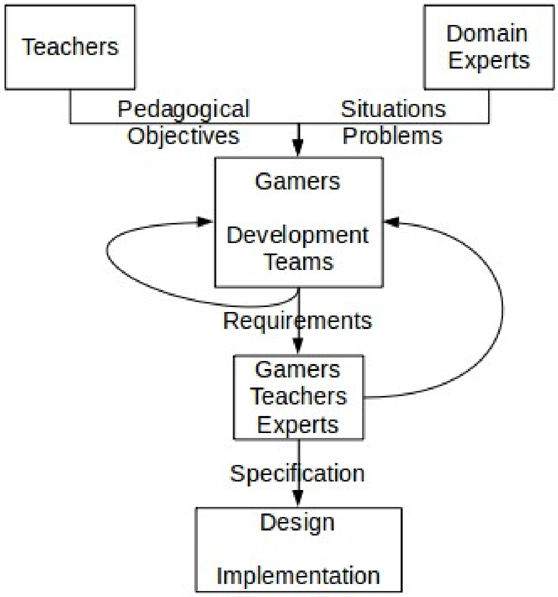

Figure 3: Process Model for the Development of Serious Games (MPDSG)

4.1. QPF Design Requirements

After performing an iterative series of interviews and focus groups with the groups of teachers, quantum computing experts and gamers, the following requirements were defined for the resulting implementation of QPF:

Pedagogical Requirements

The game should provide a visual analogy to work with quantum concepts. Looking to its use in the classroom, it should be possible to play it at short bursts and pause it when needed. It would be desirable that the game could be executed in mobile devices and 10-year-old PCs, and that it would not need a stable internet connection.

Content Requirements

The game should cover the basic aspects of quantum computing: qubits, qubit states, superposition and at least an introduction to quantum gates. Quantum game theory examples could be used as inspiration for the game design.

Gaming Requirements

The game should be fast and casual, not too long. It should fell that is an actual videogame, and not an educational tool disguised as a game. It should be able to work in an Android smartphone. The game should reward you in some way to give you feedback of how you are performing.

5. Results

5.1. The Game Design

Quantum Penny Flip (QPF) focuses on the game Penny Flip. This game is often used as a point of entry to quantum game theory, so it is the first contact between the students and many new concepts related to quantum mechanics and game theory.
In QPF, the scenario is an abstract rain of falling black or white coins (figure 4). The player is allowed to flip the coins in the upper and lower areas by tapping or clicking on them, turning them the opposite color. The player can not however affect the coins inside the area marked red at the center of the screen. That is the area the CPU plays, and it can randomly flip some coins when they are crossing the area.
The player earns points when the coins finish black at the bottom of the screen, and is penalized when they end up white. Depending on the game mode, a white coin exiting the bottom of the screen means a decrease of the score (in normal mode) or the loss of a live (in infinite mode).
From time to time, a floating "H" power up may appear, and touching it sets barriers at both sides of the red area for a limited time. All coins that cross the upper barrier turn to a half-white half-black coin, and when they cross the lower barrier they turn to a black or white coin again. The possibilities are depicted in figure 5.

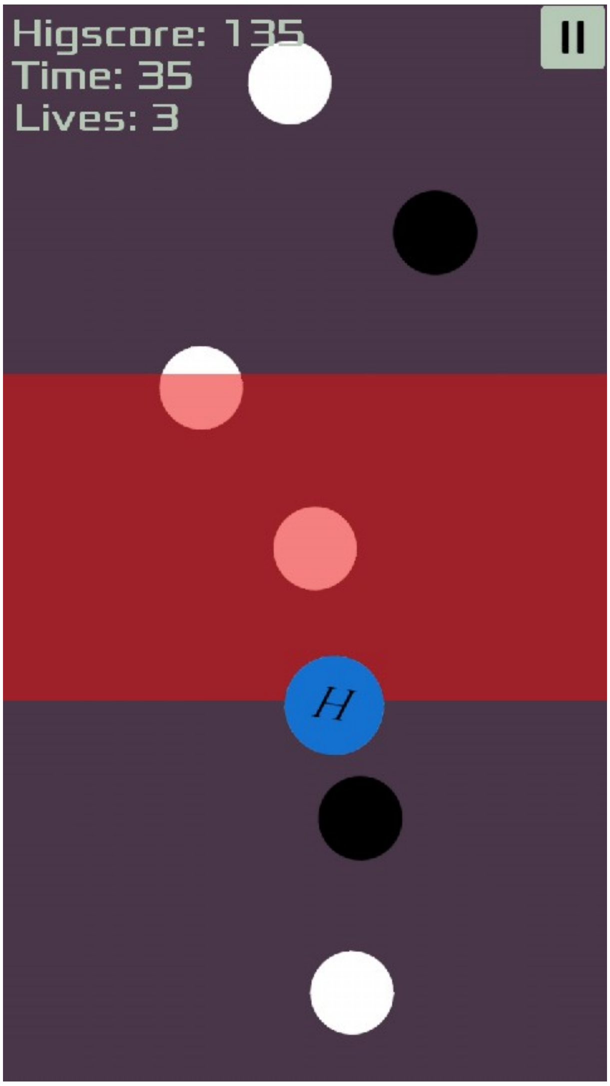

Figure 4: Quantum Penny Flip screenshot

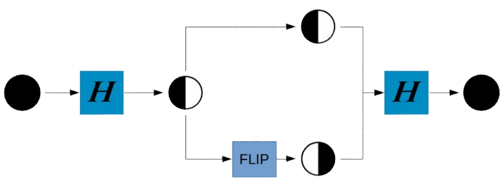

Figure 5: Hadamard gate reversibility in QPF

5.2. Game Modes

In Normal Mode, there are 24 levels that become available as they are completed by the player. The levels are increasingly difficult, adding more speed and quantity of coins as the game unfolds. Each level lasts 60 seconds, and when the level ends the player is punctuated by a number of up to 3 stars based on his performance.

In Infinity Mode, there is no time limit and the player adds up to his score until he runs out of lives. A live is lost when a white coin crosses the bottom of the screen. As the time passes in this mode, the speed and quantity of coins is increased, and the red area can sometimes slide up and down the screen.

5.3. Under the Hood: The Serious Purpose Within

The whole setup of the game is an analogy for quantum computing. The coins represent qubits, being black and white the equivalent of its |0> and |1> states. The flip action on a coin equals a NOT gate, inverting its state. The H power up is the Hadamard gate, which sets the qubit into (top barrier) and out of (lower barrier) the superposition state.

The distinct areas in the screen represent the three turns in the Penny Flip game. The player plays in the first and third turns, and the CPU plays in the second turn. As the original game, if the coin remains in |0> after the three turns, the player wins. Else, CPU wins. Applying the Hadamard gate at the barriers suppresses the changes made by the actions in the second turn, because of the property of reversibility.

5.4. Open Educational Resource

Serious games with a learning purpose can be thought of as Educational Resources. Serious games what are distributed freely and its source code made available to modify with no strings attached are Open Educational Resources (OER). The product of the work described in this article was meant from the beginning to be an OER.

5.5. Open Access

Care was taken to ensure that the game will be suitable for most audiences. For this reason, the game graphics were kept extremely simple to keep the technical requirements as low as possible. Furthermore, QPF was compiled for the most common and inexpensive gaming platforms: Windows, Linux, Android and HTML5 (web engine).

The game performance was tested on several Android mid-range phones, and netbooks using both Windows and Linux operating systems. QPF performed well in all scenarios. The HTML5 export showed to be heavier in resources, because it needs to be executed on top of a browser, but performed quite well in every case.

One fact that arose when testing on different platforms is that the game difficulty level was a lot harder when played with a mouse, compared to tapping a touch screen. The current difficulty level of the game ends to be quite easy in touch screens, and a bit hard when using a mouse. A feature to work on would be to adjust the difficulty based on the controller.

QPF was published to freely download it on Google Play Store for Android, and in our web page (gti.fi.mdp.edu.ar) for all the deployment platforms.

5.6. Open Source

QPF being totally open source was a top priority from the beginning. As we are part of a public institution, we believe that our products should be available for the society to use and further modify and personalize as needed or wanted. To that end, several measures were taken:

- QPF was developed with Godot, an open source game development engine that executes on Linux and Windows, and provides cross-compiling export to several platforms.
- The entire source code is publicly available on Github, so people can

compile, fork and pull request changes on the original code.
- An explanation of the game and the quantum computing concepts that it deals with is available on Github along with the source code.
- All media used in the game (images, sounds, etc.) are licensed under the Creative Commons Licenses, so there are no strings attached to reusing them.

6. Conclusions

This article introduced Quantum Penny Flip, an open source serious game for learning quantum computing. Care was taken to make the game freely available to play with few system requirements to get to a broad audience. Also, its source code was made publicly available to modify and redistribute with no strings attached.
The authors feel that the objectives of this work were met, but there is further work to be done regarding the evaluation and improvement of the game.

7. Future Work

In this stage we have not yet evaluated in field the use of the game. We are looking forward to test it in a class of students and to acquire data for further improvements over a series of development cycles listening to the voices of the involved groups: teacher, students and quantum computing experts.
Additionally, we are projecting to implement a set of learning analytics into the game, to record the playing experience of the students.
Lastly, we are working on creating a specific quantum module for Godot Engine, to contribute to the creation of serious games on the topic.

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