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ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ & ΤΕΧΝΟΛΟΓΙΑΣ ΥΠΟΛΟΓΙΣΤΩΝ

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Design and Development of Digital Learning Game

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ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ & ΤΕΧΝΟΛΟΓΙΑΣ ΥΠΟΛΟΓΙΣΤΩΝ

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(Υπογραφή)



Θεοφίλου Στυλιανός

Σύνοψη

Η Κβαντική Υπολογιστική είναι ένας αναδυόμενος τομέας που απαιτεί βαθιά κατανόηση των θεμελιωδών αρχών της Κβαντομηχανικής, όπως τα qubits, η υπέρθεση και οι κβαντικές πύλες. Η παρούσα διατριβή παρουσιάζει το σχεδιασμό και την ανάπτυξη ενός εκπαιδευτικού παιχνιδιού για κινητά τηλέφωνα με στόχο την εισαγωγή των φοιτητών πανεπιστημίου στα βασικά στοιχεία της Κβαντικής Υπολογιστικής, ως εναλλακτική λύση στις παραδοσιακές εκπαιδευτικές μεθόδους. Το παιχνίδι χρησιμοποιεί τεχνικές μάθησης βασισμένης στο παιχνίδι για να ενισχύσει την ενασχόληση, την κατανόηση και τη διατήρηση πληροφορίας μέσω διαδραστικών puzzle. Το παιχνίδι αναπτύχθηκε με το Flutter framework και παρέχει μια προσιτή και ευέλικτη μαθησιακή εμπειρία σε διαφορετικές πλατφόρμες κινητών συσκευών. Η διαδικασία αξιολόγησης, η οποία αποτελείται από μία Pre-Post Test μελέτη, ένα ερωτηματολόγιο ευχρηστίας, ένα ερωτηματολόγιο εμπειρίας παιχνιδιού και ένα Focus Group, έδειξε ότι το παιχνίδι βελτίωσε με επιτυχία την κατανόηση των αρχών της Κβαντικής Υπολογιστικής από τους εκπαιδευόμενους. Τα ευρήματα αναδεικνύουν τις δυνατότητες της μάθησης βασισμένης στο παιχνίδι να κάνει τις αφηρημένες επιστημονικές έννοιες πιο προσιτές και ευχάριστες.

Λέξεις-κλειδιά: Μάθηση Βασισμένη στο Παιχνίδι, Εκπαιδευτικό Παιχνίδι, Κβαντική Υπολογιστική, Κβαντική Μηχανική, Παιχνίδι για Κινητές Συσκευές, Flutter

Abstract

Quantum Computing is an emerging field that requires a deep understanding of fundamental principles of Quantum Mechanics, such as qubits, superposition, and quantum gates. This thesis presents the design and development of an educational mobile game aimed at introducing university students to the basics of Quantum Computing, as an alternative to traditional educational methods. The game employs Game-Based Learning (GBL) techniques to enhance engagement, retention, and comprehension through interactive puzzles. Developed using the Flutter framework, the game provides an accessible and flexible learning experience across different mobile platforms. The evaluation process, which consists of a Pre-Post Test study, a usability questionnaire, a game experience questionnaire and a Focus Group, demonstrated that the game successfully improved learners' understanding of quantum computing principles. The findings highlight the potential of Game-Based Learning in making abstract scientific concepts more approachable and enjoyable.

Keywords: Game-Based Learning, Educational Game, Quantum Computing, Quantum Mechanics, Mobile Game, Flutter

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1 Introduction

1.1 Motivation

Quantum computing utilizes the principles of quantum mechanics to process information and solve complex problems exponentially faster than classical computers. Quantum bits can exist in multiple states at the same time, offering great computational power, beyond the limits of classical computers. The development and widespread use of quantum computing can help in fields such as pharmaceuticals, cryptography, artificial intelligence, materials science and more. (Taylor 2024; Nagappan 2023; Wootton 2017) Since quantum computing represents a new era for computer science, opening up new prospects for accelerating scientific discoveries, learning the basic principles of quantum computing is extremely important. The reason for my involvement with quantum computing was the course 'Quantum Computing', which was offered by the Electrical and Computer Engineering Department at the University of Patras.

1.2 Research Objectives

The aim of this thesis is to create an educational game that will familiarize the learners with the basic principles of quantum computing, such as quantum bits and quantum gates. Then we will define some specifications that we would like the game to meet.

First, we want to design a simple and accessible educational game with few rules, clear objectives and easy to understand mechanics. We want learners to focus on the learning object and not get distracted or tired by the complexity of the game. (*ob1*)

The game will be aimed at university students interested in quantum computing, with no previous knowledge of quantum mechanics. For this reason, it will not go into depth, but will introduce basic concepts, such as quantum registers or some basic quantum gates. This is the second requirement for the game manual. (*ob2*)

In addition, it is desirable that the game can be played at any time and in any place, without the need for equipment or a computer, simply by using their mobile phone. The user should be able to play even when they have *limited time* (e.g. traveling, waiting for public transport, etc.), so it should be light and take a short time to play. (*ob3*)

1.3 Thesis Structure

The fourth and final objective is to make the game suitable to be played in the context of a university lecture, used as an educational tool. The game could be distributed to students during the introductory lecture of the course, or it could be used as a tool to measure their knowledge retention after a lecture - for example, whether they understand the operation of the basic quantum gates. For this reason, it should have features that measure learners' knowledge retention, such as a quiz. (*ob4*)

1.3 Thesis Structure

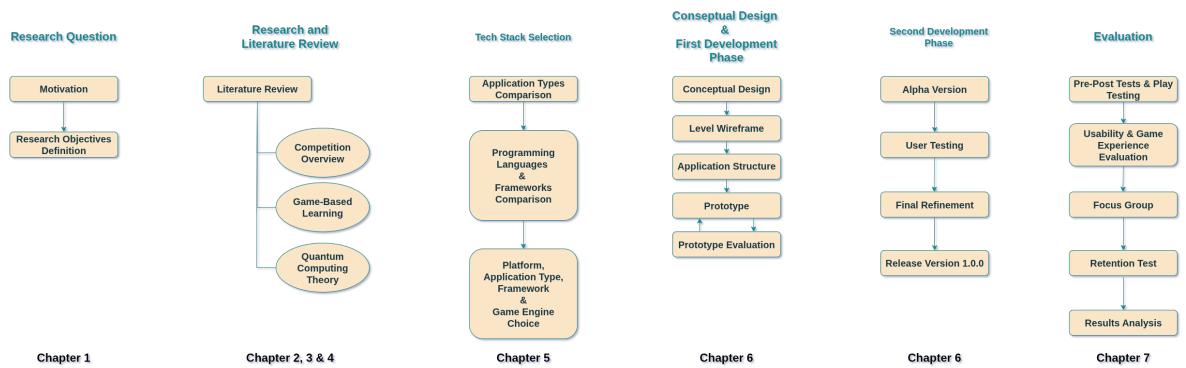


Figure 1.1. Thesis Structure.

The report consists of 7 chapters and one Appendix. The introductory chapter presents the motivation and defines the objectives of the thesis. The remaining chapters correspond to the path followed for the development of this thesis.

Chapters 2, 3 and 4 deal with the literature review. More specifically, Chapter 2 presents educational games about quantum physics, quantum mechanics and quantum computing. Chapter 3 introduces game-based learning (GBL) techniques, their advantages, the characteristics of GBL applications and some pitfalls to avoid when designing a GBL process.

Chapter 5 reviews and compares the available technologies for mobile application development and justifies the choice of the Flutter framework for our application implementation.

Chapter 6 discusses the conceptual design of the application and the adopted GBL techniques. It also presents the structure of the application, analyses the process of developing the application, and presents a high level overview of the evaluation process.

The thesis concludes with Chapter 7, which describes the evaluation process in detail. In this chapter, charts have been included to visualize the data collected and a qualitative analysis of the results is also carried out. Finally, the extracted results are presented and some suggestions for the improvement of the application are made.

In Appendix A, the screens of the application are presented in detail.

2 Literature Review

Once the goal of creating an educational game for learning quantum computing was established, a review of the available literature began. The aim of the literature review was to evaluate Game-Based Learning (GBL) as a learning modality, to document GBL techniques, and to find games related to quantum physics and quantum computing.

In this chapter, we will reason about game gender selection, based on the available literature. Also, we will present a list of educational games related to quantum physics and quantum computing, which have been the inspiration for the creation of our game.

2.1 Computer Science Games for Higher Education

In order to choose a game genre, we studied the available literature to see the approach of other researchers and to choose the most appropriate genre, according to the specifications we set in section 1.3.

According to *Batisstella (2016)*, educational games have to be engaging and motivate learners to keep playing. Their study looked at more than 100 games related to computer science, the majority of which were digital games. 97% of the digital educational games were computer games, while only 1 game was designed for mobile devices. This observation suggests a significant lack of games available for mobile devices.

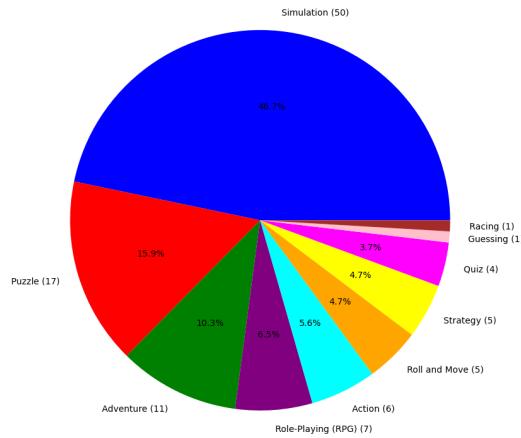


Figure 2.1. Distribution of games per genre.

Figure 2.1, which is based on the aforementioned study, shows the distribution of games per genre. The most popular genre is simulation games, followed by puzzle games and adventure games. According to the researchers, most games are single-player that don't encourage cooperation or healthy competition between learners.

2.2 Educational Puzzle Games

As we explained in section 1.3, we want the game to be easy to use and have simple mechanics. Creating a simulation game, which is the most popular genre, may lead to complex mechanics that distract the player from the educational goal. For this reason, we decided to investigate further the second most popular genre: puzzle games.

Research by *Fakokunde* (2021) on 141 subjects showed that puzzle games improved information retention, regardless of the learners' gender and cognitive style. Two other studies on puzzle games, (*Idika and Oluwaseyi 2024; Srijampana, Chebrolu, and Potti 2023*), confirm that this type of game can significantly improve information retention. They also report that they increase learners' active engagement with the material and enhance their understanding of the subject.

2.3 Educational Games for Quantum Mechanics

In the literature we can find many games for quantum mechanics, which have been developed in different contexts. The earliest game for quantum mechanics that can be found in the literature is an Atari arcade game called 'Quantum' created in 1982 (Piispanen et al. 2023). To date, more than 300 games related to quantum mechanics, digital and not, have been created (Piispanen et al. 2024). There are games developed in the context of competitions, as university coursework, by research groups, by universities, by companies, by independent enthusiasts and by professors or professional engineers. By extension, there are games that have not been developed for serious purposes, competition games, games designed for research purposes, commercial games and educational games. (Piispanen et al. 2023; Seskir et al. 2022) Due to the large number of educational games found in the literature, in this section we will focus on games developed by companies or universities with an educational purpose.

The games presented int *Table 2.1* are taken from the aforementioned studies and from the catalog on the *kiedos.art* website. (Piispanen 2024)

Πίνακας 2.1: Educational Games for Quantum Mechanics.

Game Name	Creator	Platform	Genre
<i>Quander</i> ¹	Canon Lab Org (by University of Chicago)	Web	Puzzle
<i>Collapsing Qubits</i> ²	Canon Lab Org (by University of Chicago)	Board Game	Cards
<i>Quantum Computing Playground</i> ³	Google	Web	Virtual Lab**
<i>The Qubit Game</i> ⁴	Google (Quantum AI Lab)	Web	Simulation
<i>Quantum Composer</i> ⁵	IBM	Web	Virtual Lab**
<i>Hello Quantum</i> ⁶	IBM & University of Basel	Android, iOS	Puzzle
<i>Particle in a box</i> ⁷	QPlayLearn	Web	Simulation, Puzzle
<i>Quantum Playground</i> ⁸	QPlayLearn	Web	Simulation

2.3 Educational Games for Quantum Mechanics

Game Name	Creator	Platform	Genre
<i>Q Cards⟩⁹</i>	QPlayLearn	Board Game, Android, iOS	Cards, Puzzle
<i>TiqTaqToe¹⁰</i>	QPlayLearn	Web	Strategy
<i>Psi and Delta¹¹</i>	QPlayLearn	Web	Platform, Puzzle
<i>Quantum Solitaire¹²</i>	QPlayLearn	Web	Cards
<i>Escape Quantum¹³</i>	QPlayLearn	Web	Puzzle
<i>Potatoes Quest¹⁴</i>	QPlayLearn	Web	Platform, Puzzle
<i>QWiz¹⁵</i>	QPlayLearn	Web	Puzzle
<i>Saving Photoland¹⁶</i>	QPlayLearn	Web	Puzzle
<i>Quantum Odyssey¹⁷</i>	Quarks Interactive	Web	Puzzle
<i>Quantum 3¹⁸</i>	Michigan State University	Android, iOS	Puzzle
<i>Quantum Flytrap¹⁹</i>	National University of Singapore	Web	Virtual Lab**
<i>Quantum Pattern Matching*²⁰</i>	Science At Home (by University of Aarhus)	-	Puzzle
<i>Quantum Moves 2²¹</i>	Science At Home (by University of Aarhus)	Windows, macOS, Web	Simulation
<i>Rydbergator²²</i>	Science At Home (by University of Aarhus)	Windows, macOS, Web	Simulation
<i>Network Game²³</i>	Science At Home (by University of Aarhus)	Web	Puzzle
<i>Meqanic²⁴</i>	Science At Home (by University of Aarhus)	Web, iOS	Puzzle

Game Name	Creator	Platform	Genre
<i>Quantum Kate AR</i> ²⁵	University of Southern Denmark	iOS	Simulation

[*] Under development.

[**] They are not games in the classical sense, but are treated in the literature as a game-based learning method.

¹<https://www.canonlab.org/quander>

²<https://www.canonlab.org/collapsingqubits>

³<https://experiments.withgoogle.com/quantum-computing-playground>

⁴<https://quantumai.google/education/thequbitgame>

⁵<https://quantum.ibm.com/composer>

⁶<https://hello-quantum.soft112.com>

⁷<https://qplaylearn.com/projects/quantum-physics>

⁸<https://qplaylearn.com/projects/quantum-state>

⁹<https://qplaylearn.com/projects/qubit>

¹⁰<https://qplaylearn.com/projects/superposition>

¹¹<https://qplaylearn.com/projects/wave-like-behaviour/>

¹²<https://qplaylearn.com/projects/entanglement>

¹³<https://qplaylearn.com/projects/quantum-measurement>

¹⁴<https://qplaylearn.com/projects/tunneling>

¹⁵<https://qplaylearn.com/projects/quantum-technologies>

¹⁶<https://qplaylearn.com/projects/time-frequency-modes>

¹⁷<https://ed.quantum.ieee.org/quantum-odyssey>

¹⁸<https://gamedev.msu.edu/quantum3>

¹⁹<https://quantumflytrap.com/virtual-lab>

²⁰<https://www.scienceathome.org/games/quantum-pattern-matching>

²¹<https://www.scienceathome.org/games/quantum-moves-2>

²²<https://www.scienceathome.org/games/rydbergator>

²³<https://www.scienceathome.org/games/network-game>

²⁴<https://meqanic.com/app/>

²⁵<https://apps.apple.com/ae/app/quantum-kate-ar/id1471200027>

2.3 Educational Games for Quantum Mechanics

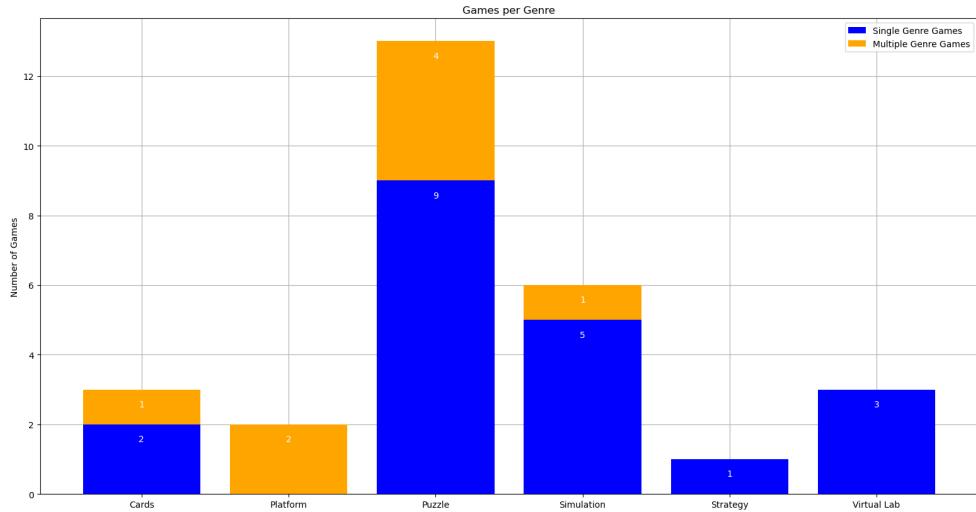


Figure 2.2. Educational games for Quantum Mechanics per genre.

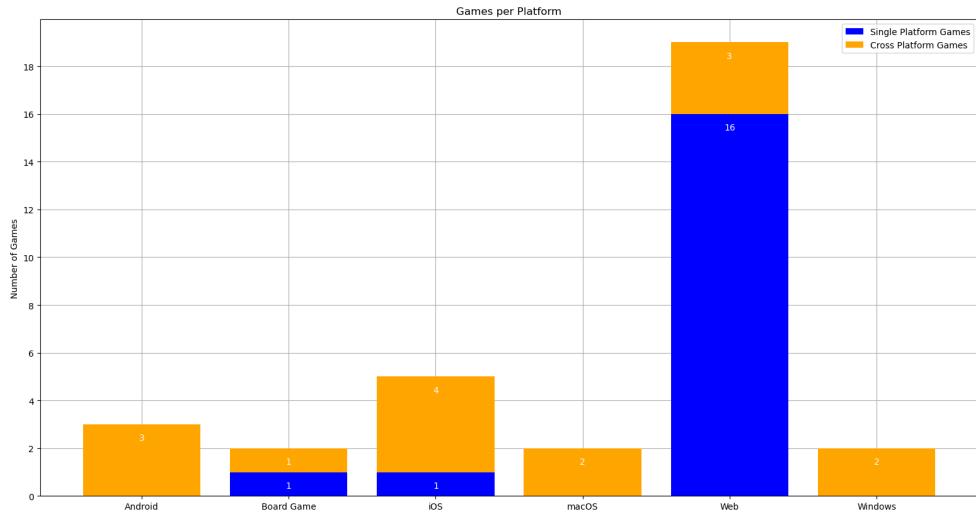


Figure 2.3. Educational games for Quantum Mechanics per platform.

In *Figure 2.2* we can see the distribution of educational games for quantum mechanics per genre. The most popular genre is puzzle games, followed by simulation games. In *Figure 2.3* we can see the distribution of educational games for quantum mechanics per platform. The most popular platform is

web, followed by iOS and Android.

2.4 Educational Mobile Games for Quantum Mechanics

As shown in *Table 2.1*, there are 5 educational games for mobile devices. 4 of them are puzzles and 1 is a simulation. We will focus on the study of puzzle games to see how the researchers approached the topic.

Unfortunately, *Hello Quantum*, *Meqanic* and *Q/Cards* are no longer available in stores, so we were unable to download them to study them. *Meqanic* was available via online simulators on Apple mobile devices (iPhone and iPad), but we were unable to find a working version; on most simulators the game wouldn't even open, and on others it crashed on the level selection screen.

Quantum 3 is available in stores, so we downloaded it on a device to study it. The game's home screen has 3 options, 'Play', 'Options' and 'Tutorial'. The 'Options' screen has basic setting for the game, such as volume control and language selection. There is also a button to clear game progress. The tutorial screen provides basic information about the theory presented in the game, as well as the mechanics of the game.

At the beginning of some levels there is a short presentation of the theory and instructions for that level. After the player has completed the level, the score is displayed. The player receives between one and three stars. The maximum score is achieved if the player completes the level in the minimum number of moves. When the level is completed, the player has the option of proceeding to the next level or returning to the home screen.

The game attempts to teach the player the composition of subatomic particles from quarks. Each level is a 2-dimensional match-3 puzzle. The player has to match three polygons of different colors to compose subatomic particles. There is no free choice of levels, a new level is unlocked each time the player completes the previous one. The game has very simple mechanics, as there are only 2 moves, selecting 3 polygons and swapping 2 polygons. It also offers the option of shuffling the board if no move is available.

2.5 Conclusions

As the literature review demonstrates, the number of educational games for quantum computing available and playable for mobile devices is limited. This gap in the market reinforces our desire to develop a game for mobile devices, as it will be easy to engage with the game during a lecture or at times when the user does not have access to a computer, as explained in the introductory chapter as well. Because we are not interested in improving collaboration or other teamwork skills at this stage,

2.5 Conclusions

we will not consider creating a multiplayer game. Finally, the strong boost to information retention from puzzle games and the possibility of using simple mechanics leads us to the decision to create a puzzle game.

3 Game-Based Learning

As we discussed in the previous chapter, we want to create an educational puzzle game, so we need to consider Game-Based Learning (GBL) techniques to integrate the educational process into the game mechanics. Continuing our literature review, we will present the benefits of GBL and some of the elements that characterize a GBL process.

3.1 What is Game-Based Learning

Game-based learning is a very old practice; it did not start with the advance of modern technology. It can be defined as the technique of being educated by playing games. It integrates the characteristics and principles of games such as elements of competition, rewards and active user engagement, into learning activities. Games can be an interactive tool that can simplify challenging concepts and help learners understand complex ideas, engaging them into educational content. ([Ledda 2012](#); [Wirtz 2023](#)).

3.2 Benefits of Game Based Learning

First, game-based learning is more appealing to children, as it appears to be a game on the surface, but in the background it has the ability to stimulate children's curiosity and capture their imagination. It is a friendlier and more accessible mean of engaging young learners with a subject than traditional methods, as it is fun and motivating.

Game-based learning also has the ability to enhance critical thinking and problem-solving, as they involve human instinct to compete and desire to succeed. Because learners often compete with other players, they have to collaborate and share ideas. They must listen to and evaluate the opinions of other players and take into account the tactics of opposing teams.

Games often require users to react quicker to stimuli, make critical decisions in a short period of time and combine knowledge acquired during the game to solve complex problems. Due to their repetitive and interactive nature, they have the ability to improve retention and increase the brain's capacity to memorize things.

3.3 Elements of GBL

Also, as games are flexible, they can be adapted to different learning styles, levels and paces, meeting individual needs and can also give instant feedback about where gaps in knowledge are or provide specific tasks for the user to help cover these areas. In this way, they can further help learners to identify their strengths and weaknesses.

Comparing games to traditional textbooks, although the latter have been used for many years with success, their revision and renewal takes a long time and is difficult and costly. The cost of reprinting, redistributing and recycling or storing old textbooks must be taken into account. Even in the case of digital textbooks, there is a significant cost of disposal and renewal. By contrast, games are very versatile, their rules can be adapted easily, and their content can be changed quickly to keep pace with technological and scientific progress.

In summary, game-based learning offers a modern, engaging and flexible approach to education. It is a great way to improve learners' critical thinking and problem-solving skills, boost their creativity and keep them engaged and motivated. Also, unlike traditional textbooks, it can be quickly and cost-effectively updated, in order to reflect new information and technological progress.

(Harding 2023; Wirtz 2023)

3.3 Elements of GBL

The following section is based on *Plass, Homer, and Kinzer (2015)* and *Shi and Shih (2015)*.

3.3.1 Game Mechanics

Mechanics determine the genre of the game and are the key element in linking the educational process to the game. They describe the type of activities the learner has to repeat throughout the game and can be of two types; learning mechanics and assessment mechanics.

3.3.2 Visual Aesthetic Design

The Visual Aesthetic Design is the process of representing information with graphic elements (information visualization). It also defines the way in which visualized feedback is provided.

3.3.3 Musical Score

The musical score includes the background sounds, the voices and haptic feedback (such as device vibration). These elements are used to direct player's attentions to important events, evoke emotions and provide feedback on player's actions.

3.3.4 Narrative Design

Unlike traditional textbooks, games allow for nonlinear narratives that evolve based on player's choices. A narrative can be a dialogue, a cutscene, a voice-over or other in-game action. Narratives provide information for learning, characters, events, quests and game rules. Their aim is to increase the player's motivation to continue playing the game.

3.3.5 Incentive System

The incentive system consists of motivational elements that rewards player's efforts and encourages them. Examples of incentives systems are point systems, leaderboards, stars, badges trophies and any other kind of reward.

3.3.6 Adaptivity

Adaptivity refers to the ability of the game to adjust to each learner's profile, enhancing engagement and learning outcomes. To achieve adaptivity, the game should provide mechanisms to modify game elements, such as problem complexity, guidance and feedback, according to player's needs.

3.3.7 Graceful Failure

Graceful failure refers to the idea that failure is not seen as a negative outcome, but rather as an essential and constructive part of the leadership process. The game can reduce the consequences of failure by encouraging players to take risks, explore and experiment, leading to increased motivation and engagement.

3.4 Pitfalls

There are some potential pitfalls that someone may face when designing game-based learning activities ([Moore-Russo, Wiss, and Grabowski 2018](#)). First, game elements may not be connected to learning objectives. Quite often the tasks are introduced without planning how they support the learning objectives. Also, sometimes the learning objectives are connected, but the context of the game is not. As a result, learners cannot retain knowledge or relate it to the subject. For game-based learning activities to be successful, learners must be able to retain and apply the knowledge they have been exposed to through the game. Furthermore, when students are focused on passing high stakes exams, participating in a gamified environment can be seen as an unnecessary obstacle ([Berkling and Thomas 2013](#)). Learners who are used to learning and assessment through conventional teaching methods

3.4 Pitfalls

and are focused on achieving high grades may feel deprived in a gamified environment. They will fill uncertainty, discomfort and may find it difficult to adapt to new rules (Nicholson 2012). Finally, using leaderboards to rank learners in comparison with others, many learners may feel disappointed or face discrimination (Domínguez et al. 2013).

4 Quantum Computing

In the previous chapters we introduced the techniques and the benefits of game-based learning, and we selected the genre of our game. We will then discuss the basic theory around quantum computing, which provided the information needed to design the theory slides presented in the game and on which the game mechanics are based.

Quantum computers are computers that perform calculations by taking advantage of quantum phenomena, such as superposition and entanglement. The quantum properties of the microcosm provide the ability to store and process larger amounts of information and perform specific calculations at higher speeds than conventional computers. Information is processed using quantum gates and quantum algorithms, analogs of which cannot exist in conventional computers. ([Karafillidis 2015](#); [Wikipedia contributors 2024f](#))

4.1 Quantum Bits

Quantum computers store information as bits. A quantum bit is a two-state system based on properties of the microcosm such as spin, energy state or the way particles oscillate and is the basic unit of information storage. ([Wikipedia contributors 2024f](#))

State 0 is represented as $|0\rangle$ and state 1 as $|1\rangle$ and are called basic or basis states and are orthogonal to each other. Because the two states belong to a vector space, Hilbert space¹, they can be multiplied by a number and added together, and the result will be a valid state. Superposition is based on this fact. ([Wikipedia contributors 2024f](#))

Each valid state can be written as:

$$|q\rangle = a|0\rangle + b|1\rangle$$

where a and b are called probability amplitudes and are complex numbers. The magnitudes of a and b are always less than one, and it holds that:

$$|a|^2 + |b|^2 = 1$$

¹https://en.wikipedia.org/wiki/Hilbert_space

4.1 Quantum Bits

The two basic states of a qubit can be represented as matrices:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

The state $|q\rangle = a|0\rangle + b|1\rangle$ can be represented using matrices as follows:

$$|q\rangle = a \begin{pmatrix} 1 \\ 0 \end{pmatrix} + b \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix}$$

The probability amplitudes, a and b, are complex numbers, so we can write the last equation in a more general form:

$$|q\rangle = e^{i\phi_a} \sin\left(\frac{\theta}{2}\right) |0\rangle + e^{i\phi_b} \cos\left(\frac{\theta}{2}\right) |1\rangle \Leftrightarrow$$

$$|q\rangle = e^{i\phi_a} \left(\sin\left(\frac{\theta}{2}\right) |0\rangle + e^{i(\phi_b - \phi_a)} \cos\left(\frac{\theta}{2}\right) |1\rangle \right)$$

If the global phase term $e^{i\phi_a}$ is omitted while the phase difference $\phi_b - \phi_a$ is called ϕ , the last equation simplifies to the following:

$$|q\rangle = \sin\left(\frac{\theta}{2}\right) |0\rangle + e^{i\phi} \cos\left(\frac{\theta}{2}\right) |1\rangle$$

The angle θ determines the magnitude of the probability amplitudes a and b, while the angle ϕ is called the phase angle and does not affect the measurement outcome. This means that two qubits differing only by a phase angle cannot be distinguished by a measurement. However, the phase angle should not be omitted, as it affects quantum computations.

The term $e^{i\phi_a}$ is called the global phase and is a mathematical artifact that can be safely ignored.

(Karafyllidis 2015)

4.1.1 Superposition

Superposition is based on the addition of two states, similar to how we would add two waves, and gives quantum computers the ability to perform parallel computations.

A classical bit can have two distinct states, 0 or 1, and can be stored by any system that has two distinct states, closed or open. All information is analyzed, stored, and processed as a sequence of 0s and 1s by classical computers.

A quantum system can be in both states simultaneously. Before we measure its state, it tends to be in the state $|q\rangle$ or $|1\rangle$. The quantum state $|q\rangle = a|0\rangle + b|1\rangle$ is a superposition of the two basic states. Measuring the state of the system destroys the superposition, so a qubit can only be found in one of the two basis states.

The outcome of the measurement is impossible to predict with certainty, as all we know are the probabilities of it being in one of the two basis states, which are given by the square of the probability amplitudes, a and b.

(Amazon Web Services, Inc. 2024b; Karafillidis 2015)

4.1.2 Quantum Entanglement

Quantum entanglement is defined as the state of two quantum systems when it cannot be written as a tensor product of their basic states. Quantum entanglement is a physical resource that can be used for the development of quantum algorithms and the execution of quantum computations. There is no classical analog of this state. When two systems are entangled, measuring the state of one reveals the state of the other, regardless of the distance between them. Essentially, the state of one quantum system depends on the state of the other. (Amazon Web Services, Inc. 2024b; Karafillidis 2015)

4.1.3 Decoherence

Superposition states are unstable and decohere so that the system becomes stable. Decoherence is an irreversible process and can be caused by external factors such as an increase in temperature or radiation. (Amazon Web Services, Inc. 2024b)

4.2 Quantum Registers

Quantum registers are an array of qubits used as memory and represent a superposition of 2^n quantum states, where n is the number of qubits. The numbering of the qubits is done from right to left or from

4.3 Quantum Gates

bottom to top. Quantum computers do not have classical circuits but perform operations by acting on bits that are within quantum registers.

The state of a quantum register with n qubits is defined as the tensor product of the states of the qubits that comprise it:

$$|q_r\rangle = |q_{n-1}\rangle \otimes \dots \otimes |q_1\rangle \otimes |q_0\rangle$$

(Karafyllidis 2015)

4.3 Quantum Gates

Quantum gates are not physical systems like classical gates, but physical processes applied to quantum bits (qubits) and registers that change their state. Additionally, information does not pass through quantum gates as it does with classical gates, since they are not part of any physical circuit with conductors. The information remains within the quantum registers, and the gates act on them by rotating their state vectors. A quantum gate can be a laser pulse or a magnetic field.

Since quantum bits are vectors in Hilbert space, quantum gates must be operators in Hilbert space. However, not all operators in Hilbert space are suitable for representing quantum gates. For an operator to be characterized as a quantum gate, it must not change the length of the state vector, only its angle, and it must not change the values of the inner products between state vectors. Thus, only unitary operators can constitute quantum gates.

(Karafyllidis 2015; Wikipedia contributors 2024f; Microsoft Corporation 2024a, 2024b)

Table 4.1 presents some of the most well-known quantum gates and the effects of their actions.

Πίνακας 4.1: Quantum Gates. (Wikipedia contributors 2024g)

Name(s)	# of qubits	Symbol(s)	Matrix
Identity, No-Op	any	I	$\begin{pmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \ddots \\ 0 & 0 & \dots & 1 \end{pmatrix}$
Pauli-X, NOT, Bit Flip	1	X, NOT, σ_x	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

Name(s)	# of qubits	Symbol(s)	Matrix
Pauli-Y	1	Y, σ_y	$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
Pauli-Z, Phase Flip	1	Z, σ_z	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
Phase	1	S, P, \sqrt{Z}	$\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$
Hadamard	1	H	$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$
Controlled-NOT, Controlled-X, Controlled Bit Flip	2	CNOT, XOR, CX	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$
Controlled-NOT, Controlled-X, Controlled Bit Flip	2	CNOT, XOR, CX	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$
Swap	2	SWAP	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

4.3.1 Identity

The identity quantum gate does not affect the state of the qubit. Its symbol is often omitted in quantum circuits.

Πίνακας 4.2: Identity Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$ 0\rangle$
$ 1\rangle$	$ 1\rangle$
$a 0\rangle + b 1\rangle$	$a 0\rangle + b 1\rangle$

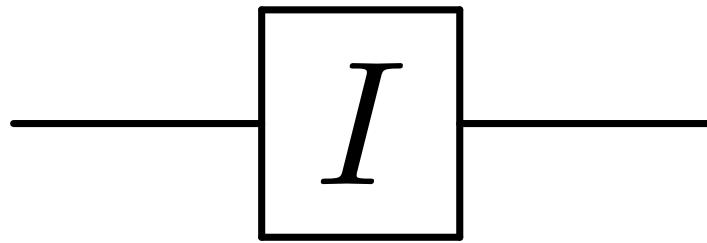


Figure 4.1. Identity Gate Circuit Diagram.

4.3.2 Pauli-X

The quantum X gate functions similarly to the classical NOT gate, rotating the state vector by 180 degrees around the X-axis. This operation changes the state from $|0\rangle$ to $|1\rangle$ and vice versa.

Πίνακας 4.3: Pauli-X Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$ 1\rangle$
$ 1\rangle$	$ 0\rangle$
$a 0\rangle + b 1\rangle$	$a 1\rangle + b 0\rangle$

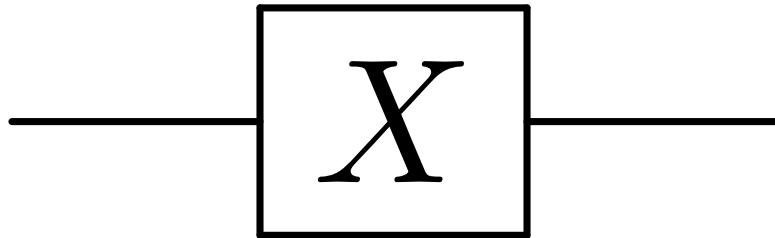


Figure 4.2. Pauli-X Gate Circuit Diagram.

4.3.3 Pauli-Y

The quantum Y gate operates similarly to the X gate but rotates the state vector by 180 degrees around the Y-axis. It changes the state from $|0\rangle$ to $|1\rangle$ and vice versa, and additionally shifts the phase of the $|0\rangle$ state by 90 degrees and the phase of the $|1\rangle$ state by -90 degrees.

Πίνακας 4.4: Pauli-Y Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$i 1\rangle$
$ 1\rangle$	$-i 0\rangle$
$a 0\rangle + b 1\rangle$	$ia 1\rangle - ib 0\rangle$

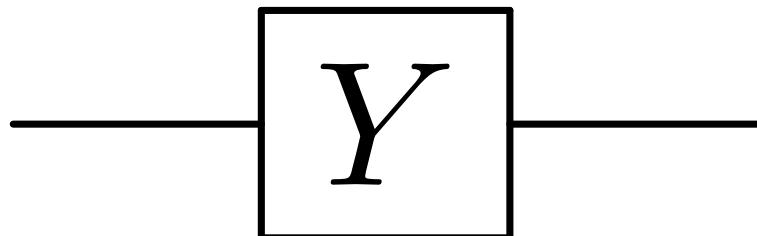


Figure 4.3. Pauli-Y Gate Circuit Diagram.

4.3.4 Pauli-Z

The quantum Z gate rotates the state vector by 180 degrees around the Z-axis. It shifts the phase of the $|1\rangle$ state by 180 degrees and does not affect the state of the $|0\rangle$ state.

Πίνακας 4.5: Pauli-Z Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$ 0\rangle$
$ 1\rangle$	$- 1\rangle$
$a 0\rangle + b 1\rangle$	$a 0\rangle - b 1\rangle$

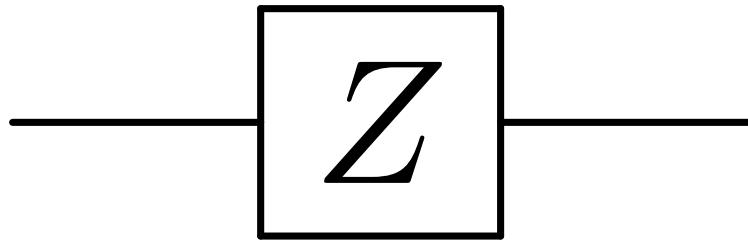


Figure 4.4. Pauli-Z Gate Circuit Diagram.

4.3.5 Phase

The S gate shifts the phase of the $|1\rangle$ state by 90 degrees.

Πίνακας 4.6: Phase Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$ 0\rangle$
$ 1\rangle$	$i 1\rangle$
$a 0\rangle + b 1\rangle$	$a 0\rangle + ib 1\rangle$

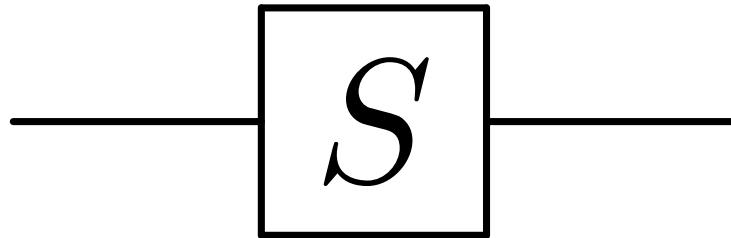


Figure 4.5. Phase Gate Circuit Diagram.

4.3.6 Hadamard

The Hadamard gate, when acting on a qubit in one of the two basis states, places it in a superposition of the two basis states. Conversely, when it acts on a qubit that is in a superposition of the two basis states, it returns it to one of the basis states.

Πίνακας 4.7: Hadamard Gate Truth Table.

$ q_i\rangle$	$ q_o\rangle$
$ 0\rangle$	$\frac{1}{\sqrt{2}} 0\rangle + \frac{1}{\sqrt{2}} 1\rangle$
$ 1\rangle$	$\frac{1}{\sqrt{2}} 0\rangle - \frac{1}{\sqrt{2}} 1\rangle$
$\frac{1}{\sqrt{2}} 0\rangle + \frac{1}{\sqrt{2}} 1\rangle$	$ 0\rangle$
$\frac{1}{\sqrt{2}} 0\rangle - \frac{1}{\sqrt{2}} 1\rangle$	$ 1\rangle$
$a 0\rangle + b 1\rangle$	$\frac{1}{\sqrt{2}}(a+b) 0\rangle + \frac{1}{\sqrt{2}}(a-b) 1\rangle$

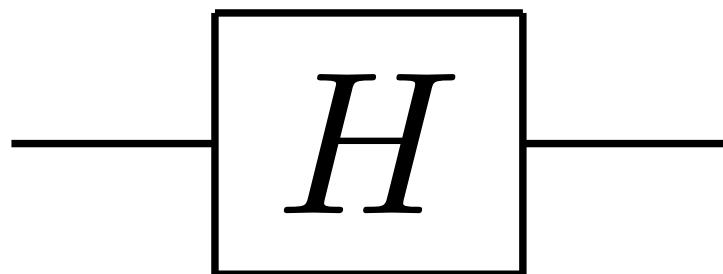


Figure 4.6. Hadamard Gate Circuit Diagram.

4.3.7 Controlled-NOT

The CNOT gate inverts the target bit when the control bit is set to 1. It functions as an X gate controlled by the control bit.

Πίνακας 4.8: Controlled-NOT Gate Truth Table - Second bit as control bit.

$ q_{control}q_{target}\rangle$	$ q_{control}q_{target}\rangle$
$ 00\rangle$	$ 00\rangle$
$ 01\rangle$	$ 01\rangle$
$ 10\rangle$	$ 11\rangle$
$ 11\rangle$	$ 10\rangle$
$a 00\rangle + b 01\rangle + c 10\rangle + d 11\rangle$	$a 00\rangle + b 01\rangle + c 11\rangle + d 10\rangle$

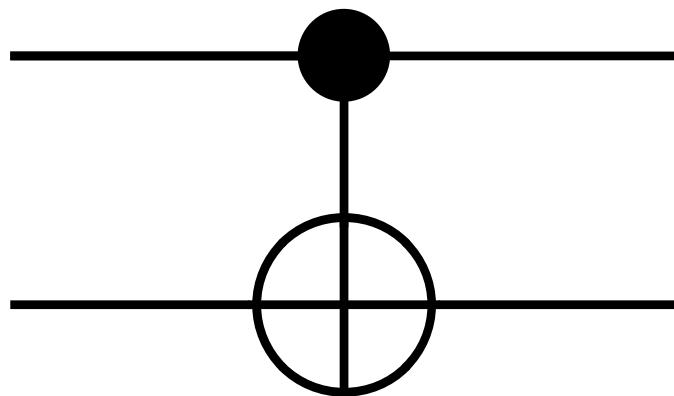


Figure 4.7. CNOT Gate Circuit Diagram - Second bit as Control bit.

Πίνακας 4.9: Controlled-NOT Gate Truth Table - First bit as control bit.

$ q_{control}q_{target}\rangle$	$ q_{control}q_{target}\rangle$
$ 00\rangle$	$ 00\rangle$
$ 01\rangle$	$ 11\rangle$
$ 10\rangle$	$ 10\rangle$
$ 11\rangle$	$ 00\rangle$
$a 00\rangle + b 01\rangle + c 10\rangle + d 11\rangle$	$a 00\rangle + b 11\rangle + c 10\rangle + d 11\rangle$

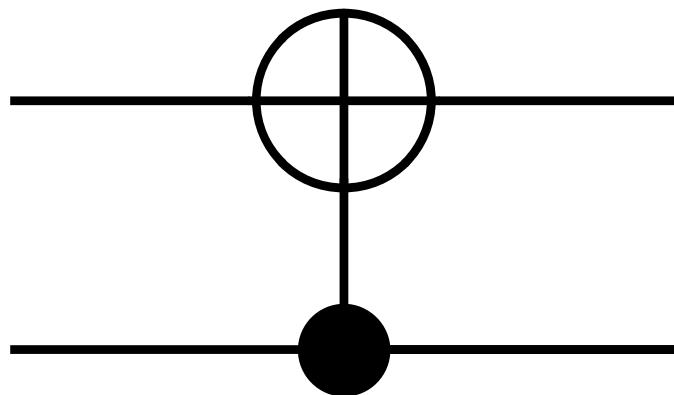


Figure 4.8. CNOT Gate Circuit Diagram - First bit as Control bit.

4.3.8 Swap

The SWAP gate exchanges the states of two qubits.

4.3 Quantum Gates

Πίνακας 4.10: SWAP Gate Truth Table.

$ q_{i1}q_{i0}\rangle$	$ q_{o1}q_{o0}\rangle$
$ 00\rangle$	$ 00\rangle$
$ 01\rangle$	$ 10\rangle$
$ 10\rangle$	$ 01\rangle$
$ 11\rangle$	$ 11\rangle$
$a 00\rangle + b 01\rangle + c 10\rangle + d 11\rangle$	$a 00\rangle + b 10\rangle + c 01\rangle + d 11\rangle$

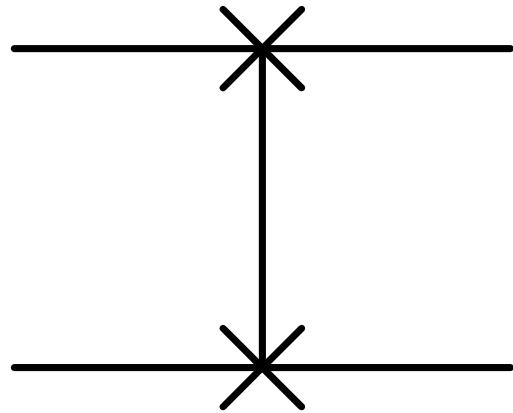


Figure 4.9. SWAP Gate Circuit Diagram.

5 Mobile Application Development

Having completed the presentation of game-based learning and the basic theory around quantum computing, it is time to evaluate the options available for the development of the application, that is, the programming language, the framework and the game engine. First, we will define mobile game development and present the available application types, and then we will review the different programming languages and available frameworks.

Mobile application development is the process of creating software applications that run on mobile devices. The software can be preinstalled on the device, downloaded from an app store or accessed through a web browser. ([Amazon Web Services, Inc. 2024a](#); [IBM Corporation 2024](#))

Mobile games are digital games designed for mobile devices. They can utilize mobile sensors and hardware (e.g. accelerometers, GPS etc.), or even external peripherals, such as gaming controllers and AR/VR headsets.

5.1 Platforms

There are two dominant operating systems for mobile devices, Google's Android and Apple's iOS. iOS is used only on Apple devices while Android is used by several manufacturers.

Developing applications on each of these platforms requires the use of different software development kits (SDKs). There are four approaches to mobile app development, which are compared below.

5.1.1 Native Applications

A native mobile application is a software application that is designed for a specific operating system platform ([Rouse 2024](#)). Native mobile apps can only work on the platform that they are designed for, because they use the programming languages, frameworks and interfaces that are platform-specific. They run directly on the operating system, so they tend to perform better than other applications that require interaction with the device's operating system or hardware.

Because native apps are compiled directly into machine code, there have to be a different code base for each version of the same application (i.e. iOS or Android version). This is a requirement that significantly

5.1 Platforms

increases the cost and time of development and maintenance. ([Amazon Web Services, Inc. 2024a; Rouse 2024](#))

Native android apps are built with the *Android SDK*¹ and use *Java*² or *Kotlin*³. On the other hand, native iOS apps are built with the *iOS SDK*⁴ and use *Swift*⁵ or *Objective-C*⁶.

5.1.2 Cross-Platform Applications

Cross-platform apps have the ability to operate on different operating systems with little to no modification. Because the use universal coding languages and frameworks, cross-platform apps can run on iOS and Android using the same codebase. These coding languages and frameworks hide from developers the underlying differences between operating systems. ([Marshall 2024](#))

Multiplatform apps reduce the cost for building and maintaining an application that targets different platforms. On the other hand, there are some performance issues and the access to device-specific features is limited, because they are not interacting directly with the operating system or the hardware. ([Marshall 2024; Amazon Web Services, Inc. 2024a](#))

According to Statista, the most popular frameworks for multiplatform development are *Flutter*⁷, *React-Native*⁸ and *Kotlin Multiplatform*⁹. ([Vailshery 2024](#))

5.1.3 Hybrid-Web Applications

A hybrid-web application combines the elements of native and web apps. They are essentially web apps that have a native app shell. They are build with standard web technologies, like *JavaScript*¹⁰ and *HTML*¹¹ and are bundled as native app packages. Hybrid apps are executed inside a container, which wraps the applications and acts as a bridge between the application and the operating system. ([Techtarget contributor 2023; Kohout 2016](#))

Although these apps reduce development and maintenance cost and user experience is very good, their performance is very low, as they cannot take advantage of many native device features. ([Amazon Web Services, Inc. 2024a; Rouse 2024](#))

¹<https://developer.android.com/studio>

²<https://dev.java/learn/getting-started/>

³<https://kotlinlang.org/docs/getting-started.html>

⁴<https://developer.apple.com/develop/>

⁵<https://developer.apple.com/swift/>

⁶<https://developer.apple.com/library/archive/documentation/Cocoa/Conceptual/ProgrammingWithObjectiveC/Introduction/Introduction.html>

⁷<https://docs.flutter.dev/>

⁸<https://reactnative.dev/>

⁹<https://kotlinlang.org/docs/multiplatform.html>

¹⁰<https://developer.mozilla.org/en-US/docs/Web/JavaScript>

¹¹<https://developer.mozilla.org/en-US/docs/Web/HTML>

5.1.4 Progressive Web Applications

Progressive Web Apps (PWAs) skip App Store delivery and conventional installation processes - they are accessible via a URL. PWAs are web apps that use browser capabilities to provide an app-like user experience, so they are written using web technologies, such as *JavaScript* and *HTML*.

PWAs are able to overcome certain disadvantages of Hybrid Web Apps, as they have better performance and more extensive access to device features. They also have low development and maintenance cost, but the app capabilities are restricted by the browser the use. ([Amazon Web Services, Inc. 2024a; Rouse 2024](#))

5.2 Languages and Frameworks

5.2.1 Android

Java

Java is a high-level, class-based, object-oriented programming language that is designed to have as few implementation dependencies as possible. *Java* applications are compiled in byte-code that can run on any *Java* Virtual Machine (JVM), meaning that compiled *Java* code can run on all platforms without the need to recompile. It was initially released in 1995. Although Android is built on the Linux kernel, which is largely written in *C*¹², the *Android* SKD uses the *Java* language as the basis for its applications. ([Wikipedia contributors 2024a](#))

Kotlin

Kotlin is a high-level, statically typed, general-purpose programming language with type inference. *Kotlin* is designed to interoperate fully with *Java* and the JVM version of *Kotlin*'s standard library depends on the *Java* class library. *Kotlin*, released by JetBrains in 2016, aims to address *Java*'s shortcomings and enhance development productivity. ([Wikipedia contributors 2024b; Fehervari 2024](#))

Comparison

Both *Java* and *Kotlin* compile to byte-code for the JVM, offering similar performance. *Java* applications tend to consume more memory, while *Kotlin* has more efficient memory management, with inline and extension functions that can reduce memory footprint. *Kotlin* has better startup time due to type

¹²([https://en.wikipedia.org/wiki/C_\(programming_language\)](https://en.wikipedia.org/wiki/C_(programming_language)))

5.2 Languages and Frameworks

interference, leading to faster initialization. Both languages support multithreading, but *Kotlin*'s coroutines simplify concurrent code handling. *Kotlin* offers modern features and capabilities for Android development while Java has stronger community support. ([GeeksforGeeks contributor 2024](#); [Fehervari 2024](#); [Medium contributor 2023](#))

5.2.2 iOS

Objective-C

Objective-C is a high-level, general-purpose, object-oriented programming language that first appeared in 1984. It is influenced by *C*¹³ and *Smalltalk*¹⁴ and it was primarily selected by *NeXT*¹⁵ for *NeXTSTEP*¹⁶ operating system. Apple chose *Objective-C* as the main programming language for iOS and macOS, because macOS was based on *NeXTSTEP*. ([Wikipedia contributors 2024c](#))

Swift

Swift is a high-level, general-purpose, multi-paradigm programming language created in 2010 by Apple. *Swift* is intended to support the core concepts of Objective-C, but in a safer way. It compiles to byte-code and uses an *LLVM compiler*¹⁷. ([Wikipedia contributors 2024d](#))

Comparison

Objective-C has more complex and verbose syntax than *Swift*. It uses square brackets and has longer syntax for method and property definitions, while *Swift* is more concise and readable, with a syntax that resembles natural language. *Swift* is also significantly faster than *Objective-C* and offers a modern framework (*SwiftUI*¹⁸) to build user interfaces. On the other hand, *Objective-C* has many well-documented, third-party frameworks and is well-tested and more stable. Also, it is a superset of *C*, so it works smoothly with *C* and *C++*¹⁹ code. ([Kaur 2023](#); [Popko 2024](#))

¹³[https://en.wikipedia.org/wiki/C_\(programming_language\)](https://en.wikipedia.org/wiki/C_(programming_language))

¹⁴<https://en.wikipedia.org/wiki/Smalltalk>

¹⁵<https://en.wikipedia.org/wiki/NeXT>

¹⁶<https://en.wikipedia.org/wiki/NeXTSTEP>

¹⁷<https://en.wikipedia.org/wiki/LLVM>

¹⁸<https://developer.apple.com/xcode/swiftui/>

¹⁹<https://en.wikipedia.org/wiki/C%2B%2B>

5.2.3 Cross-Platform Frameworks

Flutter

Flutter is a user interface (UI) SDK developed and released by Google in 2017. It can be used to create natively compiled mobile, web and desktop apps from a single codebase. It uses its own rendering engine to draw widgets on the screen, unlike other UI frameworks that rely on the platform's rendering engine or manipulate the platform's built-in UI stack. *Flutter* also provides access to native APIs. The *Dart*²⁰ programming language is used to write applications in *Flutter* and the applications are compiled ahead-of-time (AOT) on all platforms except the web, where the code is transpiled to *JavaScript* or *WebAssembly*. ([Wikipedia contributors 2024e](#); [JetBrains s.r.o. 2024](#); [Medium contributor 2024](#))

React-Native

React-Native is a UI SDK released by Meta Platforms (formerly Facebook Inc.) in 2015 and can be used to develop apps for mobile devices, Android TV, tvOS, web applications and desktop applications. Its components wrap existing native code and can interact with native APIs. *React-Native* apps are written in *JavaScript* or *TypeScript*. ([Wikipedia contributors 2024h](#); [JetBrains s.r.o. 2024](#); [Medium contributor 2024](#))

Comparison

React-Native is easier to learn, because it uses *JavaScript* as a programming language and has greater community support. On the other hand, *Flutter* has better documentation and its command line interface (CLI) offers tools that allow Continuous Integration (CI) and Continuous Development (CD) to be created more easily than *React-Native*. *Flutter*'s CLI also offers the ability to automate application deployment in the app stores. Both frameworks feature hot-reload functionality, which allows developers to see changes instantly while modifying their code, without having to recompile.

Flutter uses its own on widgets and libraries and its own rendering engine and compiles directly to native code, while *React-Native* depends on the underlying platform and uses multiple *JavaScript* layers before compiling to native code. Also, *React-Native* requires the developers to use third-party libraries, both for development and testing. These facts make *Flutter* significantly faster than *React-Native*, while allowing *Flutter* to use less CPU and memory, have a smaller package size and have more consistent UI across platforms. ([Shah 2024](#); [Bat 2024](#))

²⁰[https://en.wikipedia.org/wiki/Dart_\(programming_language\)](https://en.wikipedia.org/wiki/Dart_(programming_language))

5.3 Platform, Framework and Game Engine Choice

The application that will be developed will be a cross-platform mobile application, in order to target users using both Android and iOS. We chose to develop a cross-platform application to get optimal performance, not rely on browser limitations and have a single codebase. This choice also reduces development and maintenance costs and provides a great user experience.

Between *Flutter* and *React-Native*, we chose to use *Flutter*, because it is lighter, faster, produces smaller packages and automates the application deployment in the stores. Also, *Flutter* has its own game engine, the *Flame Game Engine*²¹, which will make the development of our game easier.

In addition, *Flutter* has libraries (e.g. *qartvm*²², *quantoools*²³) for performing quantum calculations and simulating quantum circuits, which may be useful in the game development process, while there are no corresponding libraries for *React-Native*.

²¹<https://flame-engine.org/>

²²(<https://pub.dev/packages/qartvm>

²³<https://pub.dev/packages/quantoools>

6 Conceptual Design & Development

Having explored the available educational games for quantum computers, studied GBL techniques and the basic theory around quantum computers, and chosen the framework and game engine we will use to develop the application, it is time to discuss the process that was followed to design the game up to the creation of the early prototype. Furthermore, in the last section of this chapter we will present the development timeline. *Figure 6.1* shows the process of conceptual design and implementation of the application prototype.

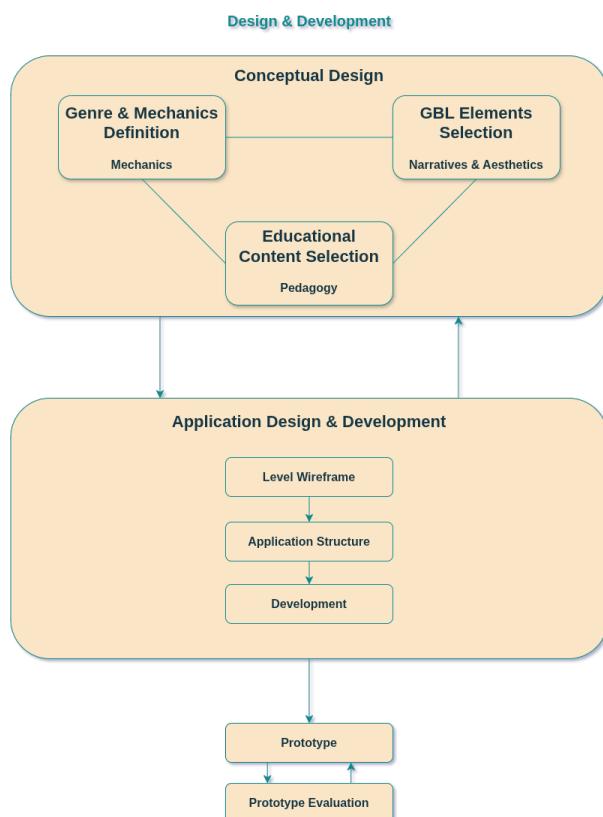


Figure 6.1. Design & Development Process.

6.1 Conceptual Design Process

According to *Kalmpourtzis* (2018), the five components of educational game design are: Mechanics, Narrative, Aesthetics, Technology and Pedagogy. These components are interconnected and should be considered when designing a game. The mechanics are the rules and procedures that guide the player's actions and the game's response to them. The narrative is the story that the game tells, the aesthetics are the visual and auditory components that make up the game's look and feel, the technology is the hardware and software that the game runs on, and the pedagogy is the educational theory that the game is based on. As for the technological part, we discussed it in the previous chapters and decided that we would build a cross-platform application using the Flutter framework and the Flame game engine. We will then present the analysis of the remaining 4 game components. As shown in *Figure 6.1*, the analysis of these elements was done in parallel and led us to define the development process we followed.

6.1.1 Genre Selection & Mechanics Definition (Mechanics)

The first step in designing the game was to determine the genre. Based on the findings in Chapter 2, we decided to make a puzzle game, as it is suitable for increasing knowledge retention while allowing for simple mechanisms.

We reasoned that a 2D shooting game, combined with a puzzle game, could have simple mechanisms, especially if the effect of gravity or other external factors on the missiles is not taken into account. This thinking led us to the decision to create a game with missiles being launched into space from a spaceship. We immediately thought that there was a similar computer game that we could use as a blueprint: *Space Invaders*¹. In this game, the player controls a laser cannon that moves horizontally across the bottom of the screen. The objective is to eliminate a group of aliens positioned above the cannon, by shooting at them. We decided to create a variation of this game, in which the player controls a spaceship and shoots missiles upward at enemy spaceships.

We then had to decide which element of the game was appropriate to introduce the concepts of quantum computing. We could control 3 variables, the position of the spaceship, the position of the enemy spaceships and the state of the missiles. In terms of controlling the state of the missiles, we thought the game would be similar to Tetris, which is still a puzzle game, but it can get tedious and eventually distract the players from the learning objective, as they have a limited time to manipulate the state of the missiles, so they may randomly affect them, with no time to recall the knowledge they have gained. After rejecting the missile state control, we considered the spaceship position control and decided to control our own spaceship rather than the opposing spaceship.

Based on the above, we decided to control the spaceship not with a traditional joystick, but with quantum gates. We decided to have distinct locations where the spaceship, and therefore the targets,

¹https://en.wikipedia.org/wiki/Space_Invaders

could be found, and to encode each location with qubit states. In this way we match the position of the spaceship to the state of a quantum register. The player chooses the gate they want and places it at a specific location. Placing the gate at this location will change the state of the respective qubit, thus affecting the position of the spaceship.

Finally, once the ship is in the correct position, the player must launch missiles to destroy the targets. That requires implementing a moving graphical element and defining the equations of motion in two-dimensional space.

6.1.2 Game-Based Learning Elements Selection (Narratives, Aesthetics)

First, we decided to use narratives to introduce the theory and rules of the game, specifically overlays that appear at the beginning of certain levels and give the student the information needed to complete the level. This approach is used in many educational games, as it allows the player to learn the rules of the game while playing. We also decided to use a Tutorial Level that would introduce some player to the basic concepts and the game mechanics.

We then decided to create an incentive system to increase the student's motivation. Based on the games we found in the literature, we decided to introduce a scoring system that awarded 1 to 3 stars for successfully completing a level. To get all 3 stars, the player must complete each level with the least number of moves. We also thought it would be good to give the player new spaceships as they progressed through the game to increase motivation and engagement. We also decided not to use a leaderboard to avoid frustration or discrimination, as discussed in Chapter 3.

Finally, we decided to adopt the graceful failure approach to allow users to experiment and try alternative ways of solving the puzzle. So we decided that there would be no immediate penalty if players made a wrong move, i.e. if they moved the spaceship to the wrong position or if a shot missed. At the end of the level, they will only receive the maximum number of stars if they have used the minimum number of moves to solve the puzzle and if all their missiles hit the target. The opposite scenario will not result in a complete failure, they will simply not receive the maximum number of stars.

6.1.3 Educational Content Selection (Pedagogy)

Together with the definition of the mechanics and the choice of the GBL elements to be used in the game, it was decided which aspects of the basic theory of quantum computing –introduced in Chapter 4 –would be presented in the game. We decided to introduce the concepts of qubit, quantum register, and quantum gate at the Tutorial Level, as these are the most basic concepts. Next, we decided to introduce Pauli gates (Pauli-X, Pauli-Y, and Pauli-Z). Our decision to focus on these specific concepts was based on our literature review, where we found that they are commonly included in multiple

6.2 Development Process

educational games. This prevalence suggests that these topics are both fundamental and approachable for learners, making them effective for introductory educational purposes. We decided that the first levels should have registers with one qubit. After the player has become familiar with the operation of these gates, we will introduce the concept of superposition for one-bit registers. Later, when the player also understands superposition, we will use registers with two qubits. There, the player will have to combine their previous knowledge to solve the puzzles.

6.2 Development Process

After determining the genre, mechanics and GBL elements that would be used in the game, selecting the educational content and designing the evaluation process, we started designing the development process. We decided that our first step would be to convert the conceptual design into a wireframe. The next step would be to define the screens of the application and the navigation flow between them (application structure). After evaluating the wireframe and the application structure, we would start developing the game. The implementation of the first two steps would allow us to create a working prototype, which would then be tested by typical users. Based on their feedback, we will improve the prototype and repeat this process until we have a satisfactory result. Then the alpha version of the game will be ready, and we will be able to conduct extensive user testing.

6.2.1 Level Wireframe

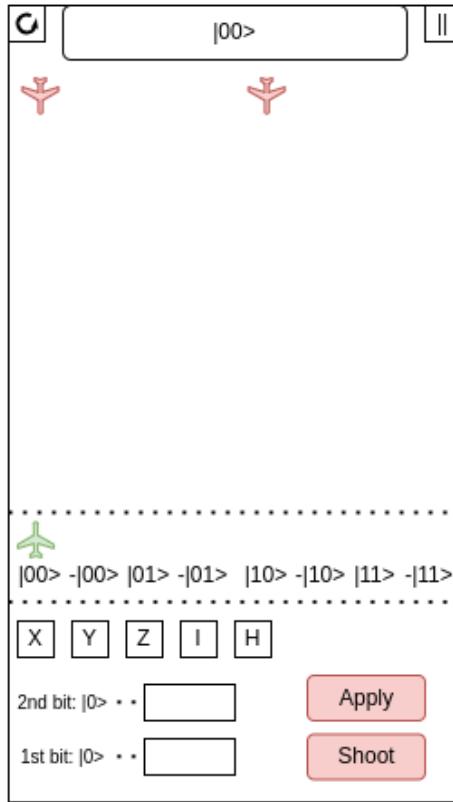


Figure 6.2. Wireframe

A prototype level (wireframe) was then designed in *diagrams.net*², which formed the foundation for creating the game's graphical interface. As shown in *Figure 6.2*, the original approach did not include a graphical element for the quantum register, but rather 2 discrete qubits to which the quantum gate would be applied. There were also two buttons, one for applying the gate and one for launching the missiles. The target state was placed at the top of the screen. Finally, the targets were enemy spaceships, as in the original *Space Invaders* game.

6.2.2 Application Structure

Figure 6.3 shows the structure of the application.

²<https://app.diagrams.net/>

6.2 Development Process

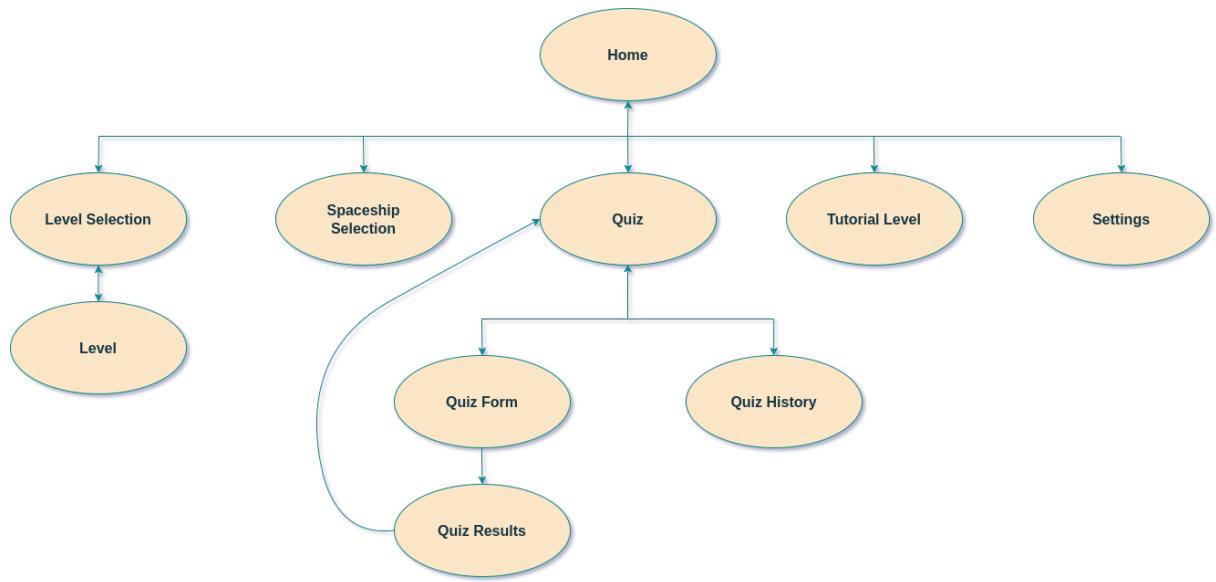


Figure 6.3. Application Structure & Navigation Flow.

The 'Home' screen will consist of 5 buttons which will navigate the user to the level selection screen, the ship selection screen, the quiz menu, the tutorial level or the settings. It will not be possible to navigate between these screens without returning to the home menu, in order to keep navigation as simple as possible and avoid too much depth.

The 'Level Selection' screen will allow the user to select one of the available levels. Each level is preceded by a tile showing the level number, the portals available and the score the player has achieved in that level.

The 'Level' screen and the 'Tutorial Level' screen will be the only screens managed by the Flame game engine and will have Flame widgets. When the user leaves these screens, the game engine will shut down.

The 'Spaceship Selection' screen will allow the user to select which spaceship to operate. Spaceships are initially locked and rewarded to the User as described in Section 6.3.

The 'Quiz' screen will provide the ability to navigate to two sub-screens, the 'Quiz Form' screen, where the user can take the quiz we have created for the evaluation needs, and the 'Quiz History' screen, where the user can view previous quiz attempts. In this way, they can see for themselves if they have improved their knowledge. After completing a quiz, the application will proceed to the 'Quiz Results' screen, where the score for that particular attempt will be displayed. We added the quiz to the application to evaluate the effectiveness of the game in teaching quantum computing concepts.

Finally, the 'Settings' screen should allow the user to change the language and to reset the progress of the game.

The final layout and functionality of the screens will be presented in Appendix A.

6.2.3 Timeline

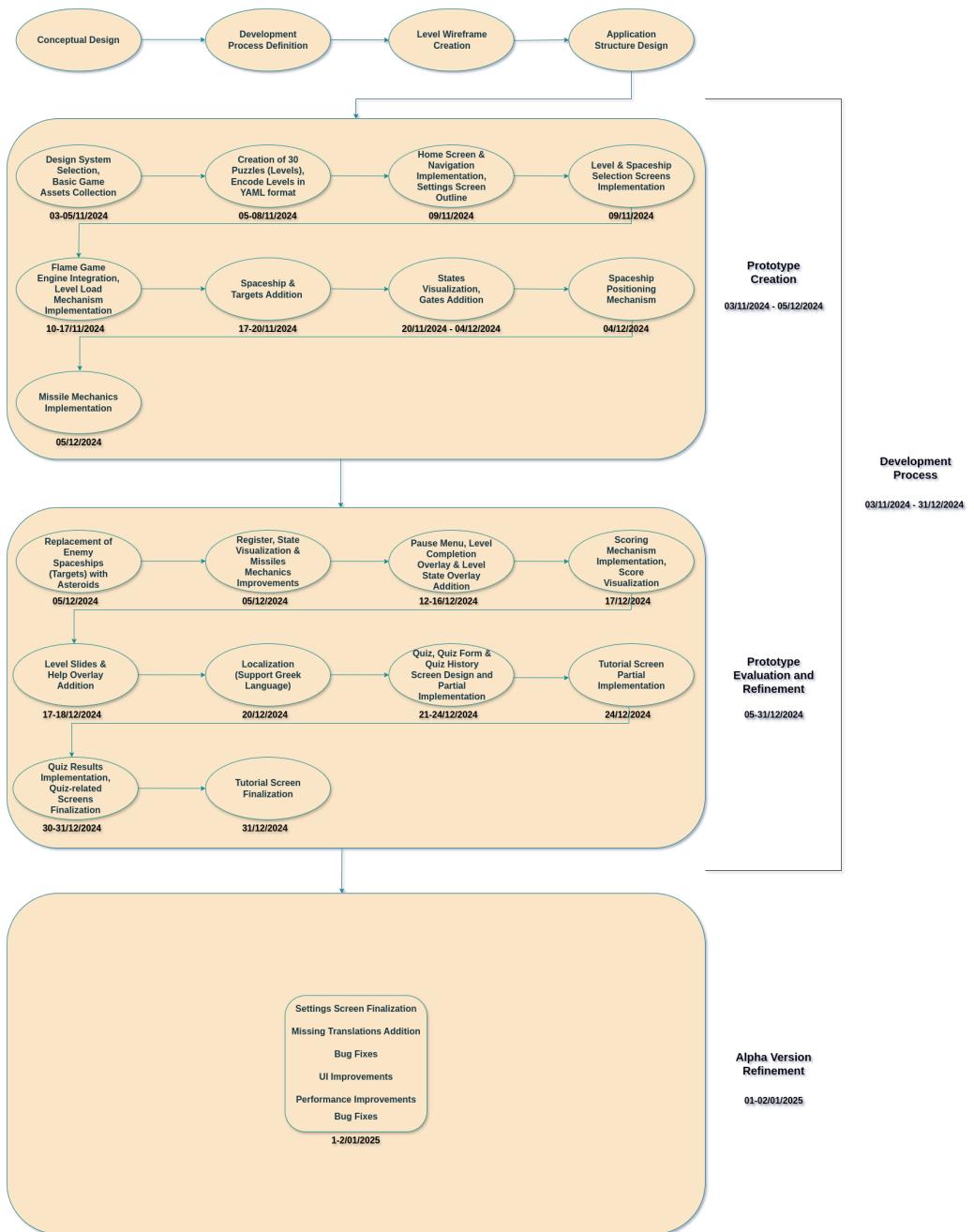


Figure 6.4. Development Timeline.

6.2 Development Process

Development of the game began in November 2024. The game developed is called *Qubity* and, as mentioned before, is a variant of the arcade video game *Space Invaders*. Google's *Material Design*³ and *Flame Game Engine*⁴ were used to create the graphical elements of the application. The spaceships, asteroids, gates and several other bitmaps used to create the sprite components of the game are from *Freepik*⁵. The background image was created by *ChatGPT*⁶ and was slightly modified.

The first step was the creation of 30 scenarios (puzzles) to form the levels of the game. The first 17 levels have a single qubit register and the available gates are Pauli-X, Pauli-Y, Pauli-Z and Hadamard. The remaining 13 levels have a register with two qubits and the available gates are Pauli-X, Pauli-Z and Hadamard. In each level there are 2, 4, or 8 different states in which the spaceship can be in, depending on the number of qubits and the available gates, as described in the previous sections. Each scenario consists of the initial state of the qubits (initial position of the spaceship), the target state (positions of the target asteroids), the available gates and the minimum number of gates to be used to solve the puzzle. The scenarios are encoded in a YAML file in a manner that is human-readable while allowing for easy addition of new levels.

³<https://m3.material.io>

⁴<https://flame-engine.org/>

⁵<https://www.freepik.com/>

⁶<https://chatgpt.com/>

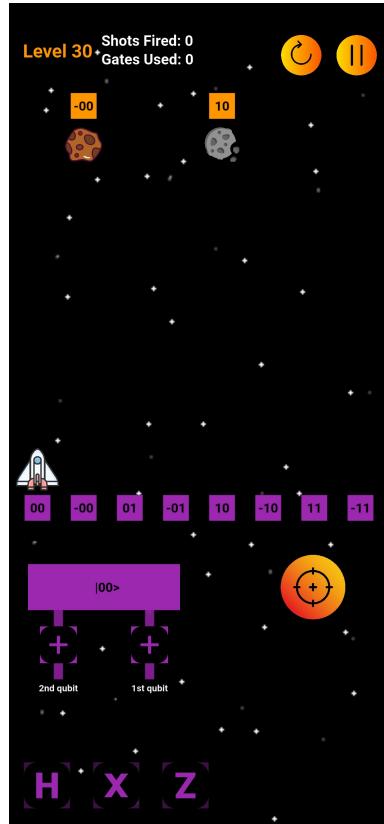


Figure 6.5. Screenshot from Level 30.

By the first week of December, the basic elements of the user interface were in place and the spaceship control mechanism was working. Then, user testing was conducted to refine the prototype, involving 5 users. Based on their feedback, the following corrections were made:

1. A graphical element was created to represent a quantum register with one or two outputs, replacing the discrete qubits. The outputs of the register represent the first or the second qubit.
2. The apply button has been removed. The gate action is applied to the register as soon as one of the register outputs is selected.
3. Targets were replaced with asteroids.
4. An overlay has been added to show the current level ID, gate used and missiles launched.
5. The target state display has been changed to make it easier of the player to understand where they need to place their spaceship.

Also, the quiz-related screens and the 'Tutorial' screen were partially implemented, theory slides were added at the beginning of some levels and help overlays were added on each level.

6.2 Development Process

In the last week of December, Greek language support was added and the 'Tutorial' screen was finalized. Also, quiz questions were created, and the 'Quiz', 'Quiz Form', 'Quiz Results' and 'Quiz History' screens were finalized. The alpha version of our application was ready.

In the following days, several bugs were fixed, and UI issues were addressed after the application was tested by 2 regular users. In addition, the 'Settings' screen was finalized, and some missing translations were added. Finally, the project was restructured a bit, and some performance issues were fixed.

7 Evaluation

Building on the conceptual design and development process described in Chapter 6, this chapter focuses on evaluating the application against the objectives we set in chapter 1, namely:

1. The game to be an effective learning tool and to successfully introduce the basic concepts of quantum computing to university students. (*ob1*)
2. The game should be enjoyable and simple so as not to distract the student from the learning objective. (*ob2*)
3. The game should be short and require no additional equipment beyond a mobile phone, making it an effective learning tool that can be utilized during a university lecture or when students have limited time. (*ob3*), (*ob4*)

The evaluation process uses a mix of methods and is divided into two parts: the first part evaluates the learning outcome of the game, while the second part evaluates the interactive system and the game experience. The evaluation of the learning outcome is based on a Pre-Post Tests methodology, while the evaluation of the interactive system and game experience are based on questionnaires and a focus group. To evaluate the application as an interactive system, we used the *System Usability Scale* questionnaire, while to evaluate the game experience we used the shortened version of the *Game User Experience Satisfaction Scale* questionnaire, the *GUESS-18*.

In addition to the aforementioned objectives, evaluating the application as an interactive system and as a game will allow us to determine whether the GBL mechanisms and elements we have incorporated into the game, namely:

1. Combination of Puzzle & Shooter mechanics
2. Narratives at the beginning of some levels
3. Incentive system
4. Graceful failure mechanism

are effective and create an enjoyable gaming experience.

Finally, we aimed to examine whether the application enhances knowledge retention. To this end, we repeated the Post Test 2 weeks after the initial tests.

7.1 Evaluation Process Description

Figure 7.1 shows the evaluation process we followed.

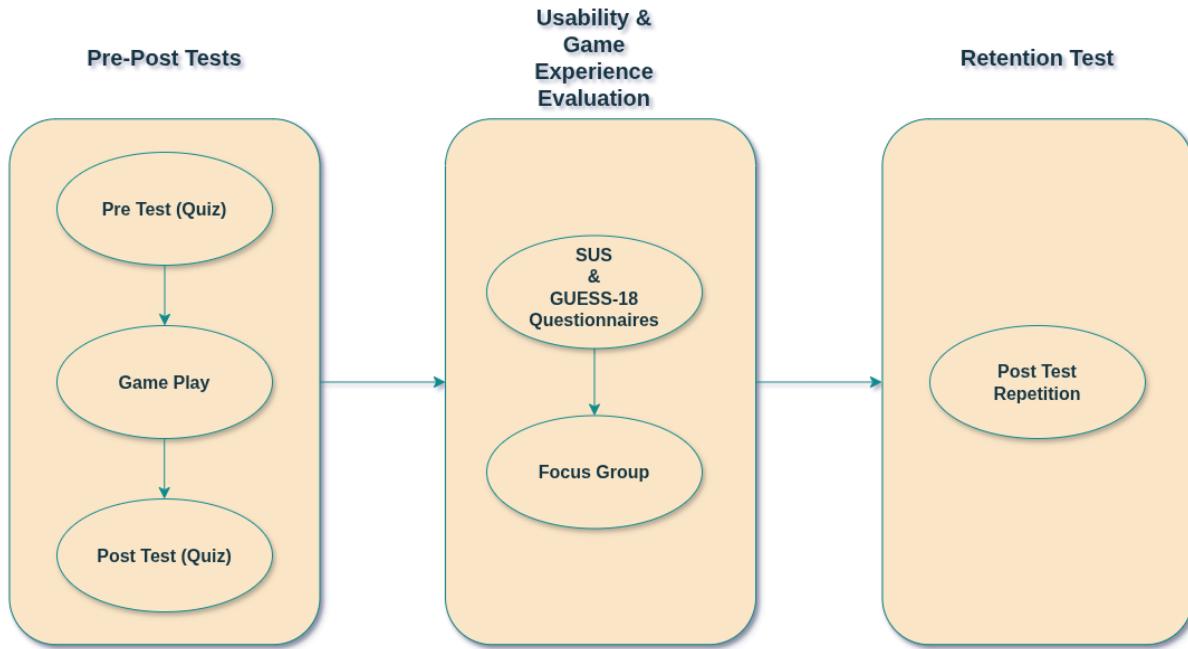


Figure 7.1. Evaluation Process.

We approached 25 university students to participate in the evaluation of the game. We sent an email containing a link to download the game and brief description of the game and the evaluation process. The email also included links to the SUS and GUESS-18 questionnaires, which they were asked to complete after playing the game. We explained in the email that we wouldn't be collecting any personal data from their devices and that the answers to the questionnaires would be anonymous. We asked from them to inform us if they were willing to participate in the evaluation process, and we received 23 positive responses.

Quiz questions are available in the *Appendix B* section of this thesis. Both SUS and GUESS-18 questionnaires are available in the *Appendix C* section of this thesis.

7.1 Evaluation Process Description

7.1.1 Evaluation of Learning Outcome

The first phase of the evaluation was based on the Pre-Post approach, as described by *Cooksey and Jonsson (2022)* and *Stratton (2019)*. We started by creating a repository of candidate questions to help structure the quiz. These questions were mainly taken from comprehension quizzes given in the

Quantum Computation course at the University of Patras (academic year 2023-24, lecturers: Sgarbas, K. and Kounavis, P.). A subset of these questions was then selected and adapted to the content of the game. The quiz consists of 3 theoretical questions and 9 questions regarding quantum gates actions. Each correct answer awards one point, while each incorrect answer gives zero points. The theoretical questions relate to the theory presented to the player via slides. The quantum gates related questions ask the player to calculate the new state of a qubit after the gate has been applied to it, or ask the player to select the appropriate gate to perform a quantum calculation. The questions are designed to prove that the player has learned to use -some of- the gates introduced in chapter 4 and understands the concept of superposition.

As suggested by *Cooksey and Jonsson (2022)* and *Stratton (2019)*, participants were asked to complete the Pre Test before interacting with the game to get an overview of their previous knowledge. Then, they were asked to complete the tutorial level and then complete the 30 levels of the game and retake the quiz. Players were given as much time as they wanted and were asked to record how long it took to complete the game, from the moment they started playing the tutorial level until the moment they completed the last level. The time spent on the quiz was not included in this measurement. There was no further guidance on how the game works and no external help was provided to solve the levels. The *Normalized Gain* metric was used to measure efficiency, as suggested by *Cooksey and Jonsson (2022)* and *McKagan, Sayre and Madsen (2022)*.

7.1.2 Evaluation of the Interactive System

The participants who completed the Pre-Post Tests were asked to answer the SUS questionnaire.

SUS is a 10-item, 5-point Likert scale questionnaire that measures the usability of a system. The items are scored on a scale from 1 to 5, with 1 being “strongly disagree” and 5 being “strongly agree”. The scores are then converted to a score out of 100. Half of the items are positively worded and half are negatively worded. The positively worded items are scored by subtracting 1 from the score, while the negatively worded items are scored by subtracting the score from 5. The scores for each item are then summed and multiplied by 2.5 to convert them to a score out of 100. The SUS score is not a percentage, but it can be interpreted as a percentage for comparison purposes. A score of 68% is considered average, while a score above 80% is considered excellent. (*Brooke 1995; Bangor, Kortum, and Miller 2009*)

7.1.3 Evaluation of the Game Experience

After completing the SUS questionnaire, the participants were asked to answer the GUESS-18 questionnaire. The GUESS-18 is a shortened version of the GUESS questionnaire, and is an 18-item, 7-point Likert scale questionnaire that measures the game experience. We chose the shortened version to prevent survey fatigue. The items are scored on a scale from 1 to 7, with 1 being “strongly disagree”

7.2 Results

and 7 being “strongly agree”. The scores are then converted to a score out of 100. The GUESS-18 questionnaire is divided into 9 subscales. Each subscale has its own score, which can be used to measure the overall game experience. (Phan, Keebler, and Chaparro 2016; Keebler et al. 2020)

7.1.4 Focus Group

A subset of 8 participants from the initial 23 players took part in the focus group. The discussion focused on four key areas: *User Interface & User Experience* (UI & UX), *Game Mechanics*, *Difficulty*, and *Scoring & Rewards*. Participants were also encouraged to share their overall impressions of the application and engage in open discussions with one another. Insights gathered from the focus group will inform future improvements to the game. The questions they were asked to discuss were related to 4 areas; *User Interface & User Experience* (UI & UX), *Game Mechanics*, *Difficulty* and *Scoring & Rewards*. They were also free to discuss with each other and comment on their overall experience of the application. The findings from the focus group will be used to improve the game in the future.

The focus group was conducted via Zoom meeting, lasted about 1 hour and was neither recorded nor transcribed. The focus group had no strict structure. The users were free to discuss each of the 4 areas of interest for about 10 to 12 minutes per area under the supervision of the researcher who took notes. Follow-up questions were then asked for clarification. In addition, the supervisor encouraged individuals who were not participating as actively to share their views. (Rabiee 2004; Wilkinson 1998)

7.1.5 Retention Test

Two weeks after the first evaluation, the participants were asked to complete the same quiz they had completed in the first evaluation. A subset of 10 participants from the initial 23 players took part in this test. The aim of this test was to measure the retention of knowledge acquired through the game. The participants were asked to complete the quiz without playing the game again, and they were not given any additional information about the quiz or the game. The time spent on the quiz was not included in this measurement. The results of this test will be compared with the results of the first Pre Test to determine whether the game has a positive effect on knowledge retention.

7.2 Results

In this section we present the results of the evaluation process described in *Section 7.1*. The results are divided into four sections: *Learning Outcome*, *Interactive System*, *Game Experience* and *Focus Group*. Each section presents the results of the evaluation process and discusses the findings. Because of the small sample size, we do not perform any statistical analysis of the results. The results are presented qualitatively and also in graphical form, to help visualize the findings.

7.2.1 Learning Outcome

To measure the effectiveness of the application as a learning tool, we used the *Normalized Gain* metric. It is calculated as the ratio of the actual average gain to the maximum possible gain.

The *Normalized Gain* (Cooksey and Jonsson 2022; McKagan, Sayre, and Madsen 2022) for each individual player is calculated as follows:

$$g = \frac{post\% - pre\%}{100\% - pre\%}$$

Where:

- $pre\%$: player's score in the quiz before playing the game (Pre Test)
- $post\%$: player's score in the quiz after playing the game (Post Test)
- $100\% - pre\%$: maximum possible gain, since score is capped at 100%

The *Average Normalized Gain* is defined as:

$$\langle g \rangle = \frac{\langle post\% \rangle - \langle pre\% \rangle}{100\% - \langle pre\% \rangle}$$

Where:

- $\langle pre\% \rangle$: average score of all players in the quiz before playing the game (Pre Test)
- $\langle post\% \rangle$: average score of all players in the quiz after playing the game (Post Test)

In *Figure 7.2* we can see the players' score in the quiz before playing the game (blue - left bars) and the players' score after they completed the game (orange - right bars). We can observe a significant improvement in players' scores after completing the game. For instance, the average player score before the game was about 17% and after the game it was slightly above 75%. This is an encouraging result and an indication that the game is effective as a learning tool.

The *Average Normalized Gain* ($\langle g \rangle$) was 0.7, which indicates a substantial improvement in the players' knowledge after playing the game. According to the literature, an average gain above 0.25 is considered effective (Cooksey and Jonsson 2022), making this result particularly significant. This demonstrates the game's effectiveness as an educational tool and highlights its potential to significantly enhance learning outcomes.

7.2 Results

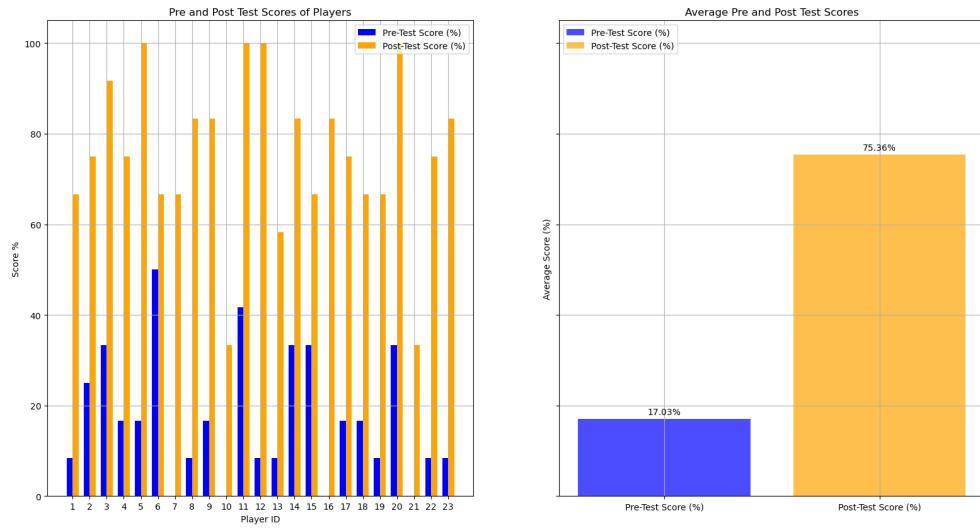


Figure 7.2. Score Improvement.

As part of the analysis of the results, we also asked the following question; Does the initial score - and therefore any prior knowledge of the players - affect the final score? In *Figure 7.3*, we attempt to correlate the initial score with the final score, and we observe a moderate positive correlation between the two variables.

Participants who scored above 90% had attended university courses in Physics and Computer Science, making them more familiar with concepts such as superposition, gates, and registers. The two participants with the lowest performance in the Post Test had the same level of mathematical knowledge as the others but had not attended courses in Physics or Computer Science. The remaining participants had the same level of mathematical knowledge and had attended Computer Science courses but did not have the same academic background in Physics as those who achieved a Post Test score above 90%.

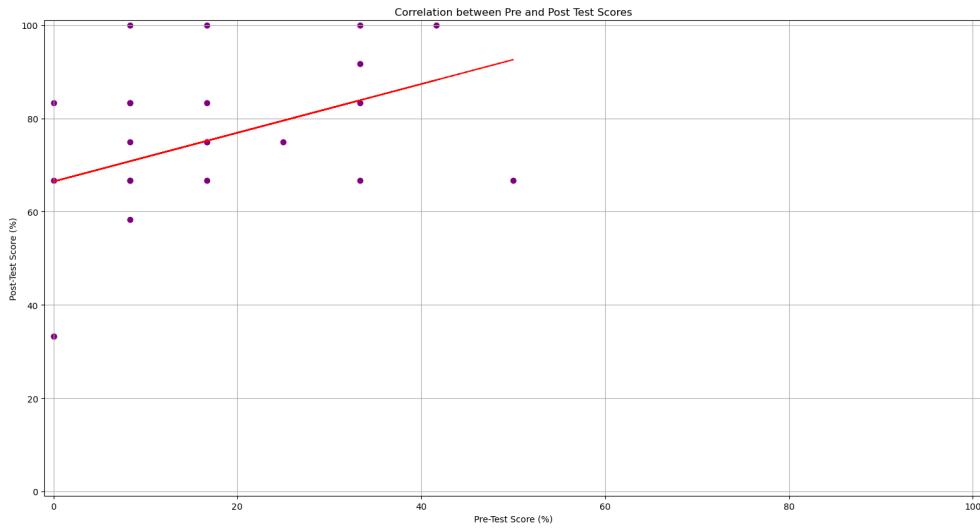


Figure 7.3. Correlation between Pre Test and Post Test Scores.

We then examined whether the time taken by players to complete the game affected their understanding of the object and thus their final score. We don't observe any significant correlation between the time taken to complete the game and the final score, as shown in *Figure 7.4*. The average time it took players to complete the game was 18 minutes.

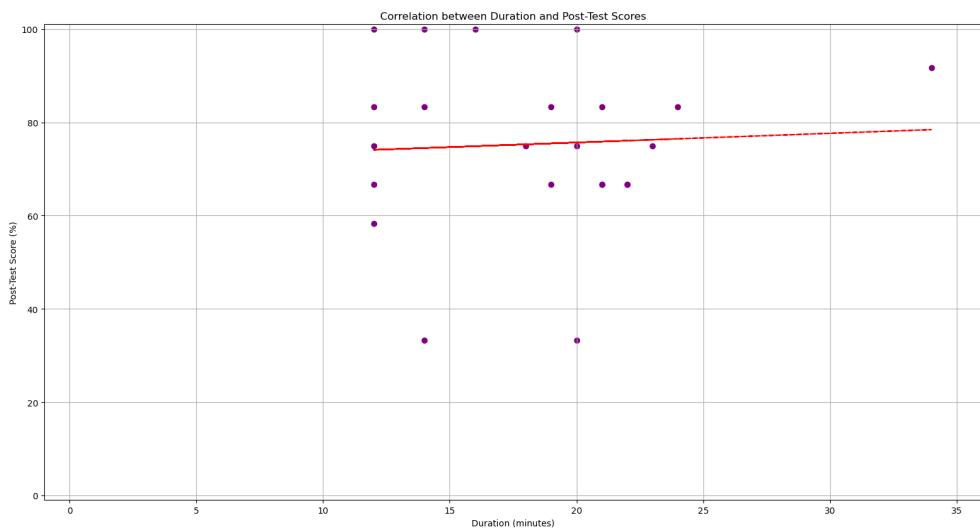


Figure 7.4. Correlation between Duration and Post Test Scores.

7.2 Results

Finally, we performed a paired t-test¹ to compare the Pre Test and Post Test Scores. The Null Hypothesis (H_0) states that there is no significant difference between the two means, while the Alternative Hypothesis (H_1) states that there is a significant difference. The t-test results in a $t-value$ of 15.591 and a $p-value$ of less than 0.001 for a Significance Level $\alpha = 0.05$, indicating that we can reject the Null Hypothesis with high confidence and conclude that the difference between the means is statistically significant. This further supports the effectiveness of the game as a learning tool.

7.2.2 Interactive System

As described in *Section 7.1.2*, we used the SUS questionnaire to evaluate the usability of the application. The SUS score for each participant is calculated using the following formula (Lewis 2018):

$$SUS = 2.5(20 + \sum (w_{01}, w_{03}, w_{05}, w_{07}, w_{09}) - \sum (w_{02}, w_{04}, w_{06}, w_{08}, w_{10}))$$

Where w_i is the weight of the answer to the $i-th$ question (1-5).

To determine the overall SUS score, we calculate the average SUS score across all participants using the formula:

$$\langle SUS \rangle = \frac{1}{N} \sum_{i=1}^N SUS_i$$

Where N is the number of participants and SUS_i is the SUS score of the $i-th$ participant.

The SUS score of our application is 86.33, which is classified as *Excellent* on the *Bangor adjective rating scale* (2009) and corresponds to the highest grade, *A+*, on the *Sauro-Lewis curved rating scale* (2011; 2016). These results indicate that the application is highly usable and provides a positive user experience. The findings will be compared with the focus group findings.

7.2.3 Game Experience

As described in *Section 7.1.3*, we used the GUESS-18 questionnaire to evaluate the game experience. The ratings within each subscale are averaged to obtain a subscale score, and the composite score of game satisfaction can be calculated by summing subscale scores together. The answer to the question “*I feel bored while playing the game*” in the *Enjoyment* subscale needs to be reverse coded (i.e. subtract the score from 8). The scores were calculated using the spreadsheet created by Keebler et al. (2020). The polygon chart in *Figure 7.6* was created using the same spreadsheet.

¹<https://www.statskingdom.com/paired-t-test-calculator.html>

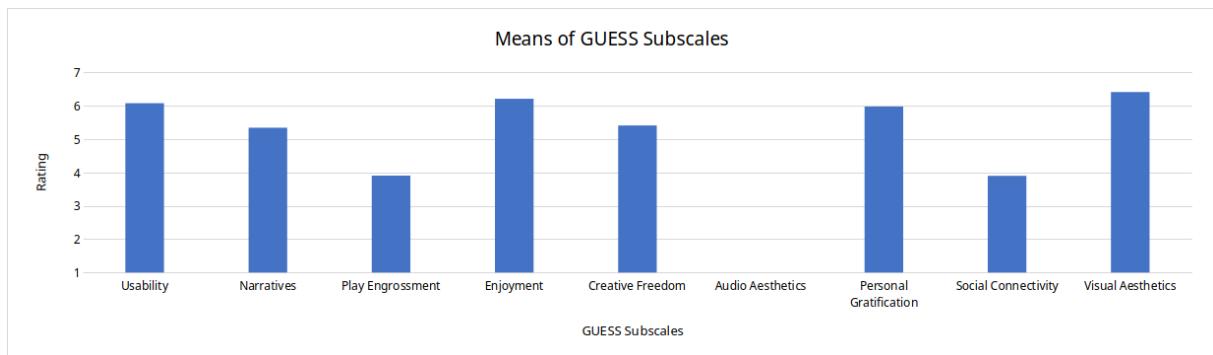


Figure 7.5. GUESS-18 Subscale Score.

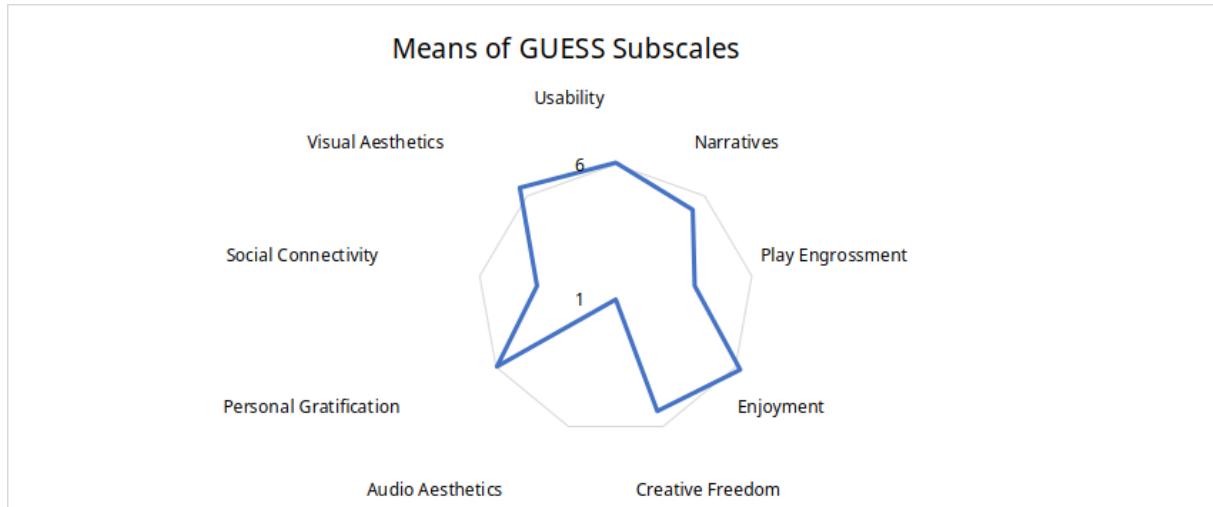


Figure 7.6. GUESS-18 Subscale Score - Polygon Chart.

The high scores on the *Visual Aesthetics* (6.4) and *Enjoyment* (6.2) subscales indicate that the game was enjoyable, fun, and had well-designed and consistent graphics.

The game scored 6 on the *Usability* subscale, indicates that the game was easy to use and navigate, which is consistent with the SUS questionnaire score.

Furthermore, the score on the *Personal Gratification* subscale, which is very close to 6, indicates that players felt satisfied playing the game, which is consistent with the high score on the *Enjoyment* subscale, while indicating that the game's incentive system was effective.

The score for the *Creative Freedom* subscale (5.4) is satisfactory, as players were able to choose how to solve the game's problems, which is consistent with the approach of the graceful failure mechanism incorporated into the game. The score for the *Narratives* subscale (5.3) indicates that players found the

7.2 Results

stories incorporated into the games useful, but could be more interesting and add more value to the game.

A relatively lower score on *Play Engrossment* subscale (3.9) indicates that players were not fully immersed or focused on the gameplay. This could be an area for improvement, perhaps by enhancing the challenge or adding more dynamic elements.

A moderate score on the *Social Connectivity* subscale (3.9) is expected, since the game is a single-player game and does not have any social features. Finally, the lowest possible score on the *Audio Aesthetics* subscale (1), is expected, since the game does not have any audio features.

These findings will be compared with the focus group findings.

7.2.4 Focus Group

The focus group findings align closely with the results of the GUESS-18 questionnaire, highlighting both strengths and areas for improvement in the game experience.

The high scores on the *Visual Aesthetics* and *Enjoyment* subscales of the questionnaire are consistent with the focus group feedback, where players praised the simplicity of the mechanics and the ease of navigation. Similarly, the *Usability* subscale score aligns with the focus group's positive remarks about the flawless state of the application and predictable navigation. The high score on the *Personal Gratification* subscale indicates that players felt satisfied and motivated by the game's reward mechanisms. This is consistent with the focus group findings, where players agreed that the incentive system encouraged them to improve and that unlocking spaceships provided a sense of reward and motivation to continue playing.

On the other hand, the relatively low scores on *Play Engrossment* and *Audio Aesthetics* are echoed in the focus group's suggestions to add background music and sound effects to enhance immersion. Additionally, the request for more challenging puzzles and hints aligns with the moderate score on *Creative Freedom*, suggesting room for improvement in providing more engaging and dynamic gameplay.

In the following sections we will present the focus group findings by area.

User Interface & User Experience

- One player requested an extra slide in the tutorial or in the first level, explaining how each level's score is calculated.
- One player requested that the *Next Level* button should be a different color to others (on the level completion overlay).

- One player requested to group levels in the level selection menu by difficulty.
- Players agreed that the game menu was easy to use and that the navigation worked well and was predictable.
- Players agreed that the state of the application was updating correctly. No bugs or crashes were reported.
- Some players requested to add background music and sounds when launching missiles and hitting the targets.

Game Mechanics

- Players found the mechanics simple and casual and commented that this simplicity helped them focus on solving the puzzles.

Difficulty

- Players agreed that the game is easy and intended of users with no quantum computer experience. All of them could complete all 30 levels. They said they would like to try more difficult puzzles.
- Most players said that the hardest level was level 30 (the final one), as it required a combination of 3 gates to solve the puzzle.
- One player did not understand how the Hadamard gate acts on 2 qubits. Half of the players said they would like more information about superposition, but agreed that the theory presented was sufficient to solve the puzzles.
- One player suggested that there should be hints to use in case you find it difficult to solve the puzzle.

Scoring & Rewards

- Players agreed that having a score system encouraged them to improve. 7 out of 8 players tried to complete all levels with 3 stars.
- Players agreed that they felt rewarded and motivated to keep playing by unlocking new spaceships as they progressed.

7.3 Conclusions

7.2.5 Retention Test

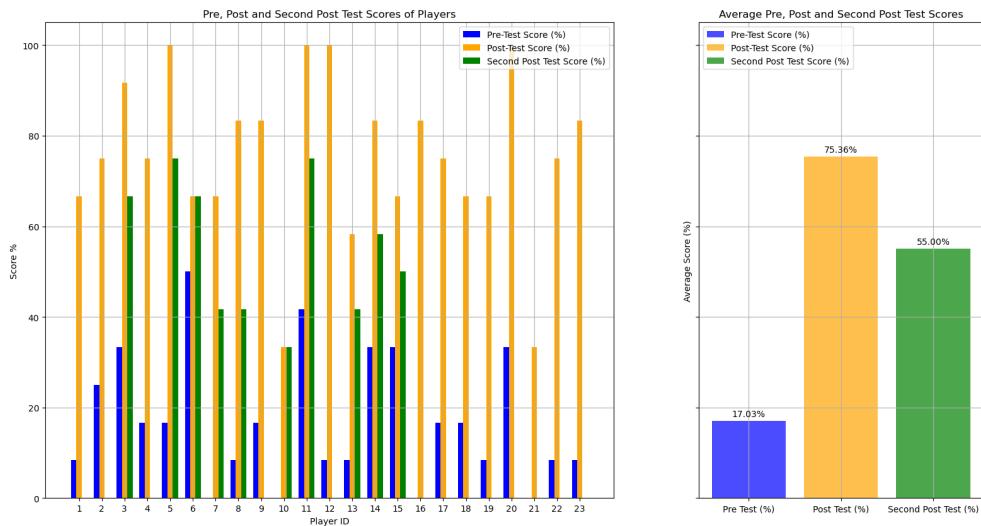


Figure 7.7. Retention Test Results.

The results of the retention test are shown in *Figure 7.7*. As mentioned in *Section 7.1.5*, 10 out of 23 participants took part in the retention test. The average score of the players in the retention test was 55%, which is lower than the average score of 75% in the Post Test. The average score of 55% is significantly higher than the average score of 17% in the Pre Test, indicating that players retained most of the knowledge acquired through the game.

7.3 Conclusions

The findings from the Pre-Post Test, Questionnaires and Focus Group collectively indicate that the game is an effective educational tool for introducing university students to the basic concepts of quantum computing. A significant improvement in knowledge has been observed, with an **Average Normalized Gain of 0.7** and statistically significant differences between the Pre- and Post-Test scores (*ob1*). In addition, retention test results revealed that players **retained much of what they had learned**. Players took an **average of 18 minutes to complete the game** -excluding the quiz-, making it suitable for use as a complementary learning tool or as a way to increase student engagement and interest for the subject (*ob3*), (*ob4*). The game was found to be **enjoyable and accessible**, with **simple mechanics and predictable navigation** (*ob1*). The built-in incentive system was **motivating and encouraged player improvement** (*ob1*). Usability was rated as **excellent**, supported by a **SUS score of 86.33** and confirmed by positive

feedback from the Focus Group and GUESS-18 scores. Overall, the game provided a **highly positive user experience**, scoring high in Visual Aesthetics, Enjoyment, Usability, and Personal Gratification, with moderate ratings in Creative Freedom and Narratives (*ob1*). Finally, the difficulty level was appropriate for beginners, and some participants expressed a desire for more challenging content (*ob2*).

On the other hand, the game lacks audio effects and social connectivity features, which could enhance player immersion and engagement. Also, adding more levels and complex puzzles would provide players with greater challenges and improve the learning experience. Some players were able to score above 9% in the Post Test, indicating that the game is not challenging enough for players with prior knowledge around Physics and Computer Science. Finally, the focus group participants expressed a desire for more information on superposition and hints to help them solve difficult puzzles, so the narratives could be expanded to provide more information about the concepts of quantum computing presented in the game.

In conclusion, all the objectives set in Chapter 1 have been achieved, and the game can be considered an effective educational tool that provides an enjoyable gaming experience, enhances knowledge retention and could be used in university lectures as a complementary learning tool. However, there is room for improvement, and the game can be further expanded to include more levels, more complex puzzles, and additional features to enhance user experience and introduce more advanced concepts of quantum computing.

8 Conclusions and Future Work

8.1 Overview

The aim of this thesis was to develop an educational game for mobile devices, which will introduce learners to the basic principles of Quantum Computing. The main objectives of the thesis were:

1. The game to be an effective learning tool and to successfully introduce the basic concepts of quantum computing to university students.
2. The game should be enjoyable and simple so as not to distract the student from the learning objective.
3. The game should be short and require no additional equipment beyond a mobile phone, making it an effective learning tool that can be utilized during a university lecture or when students have limited time.

The five components of educational game design that should be considered, according to the literature, are:

1. Mechanics
2. Narrative
3. Aesthetics
4. Technology
5. Pedagogy

The development of the application followed was an iterative process, as shown in *Figure 8.1* and discussed in *Chapter 6*.

8.1 Overview

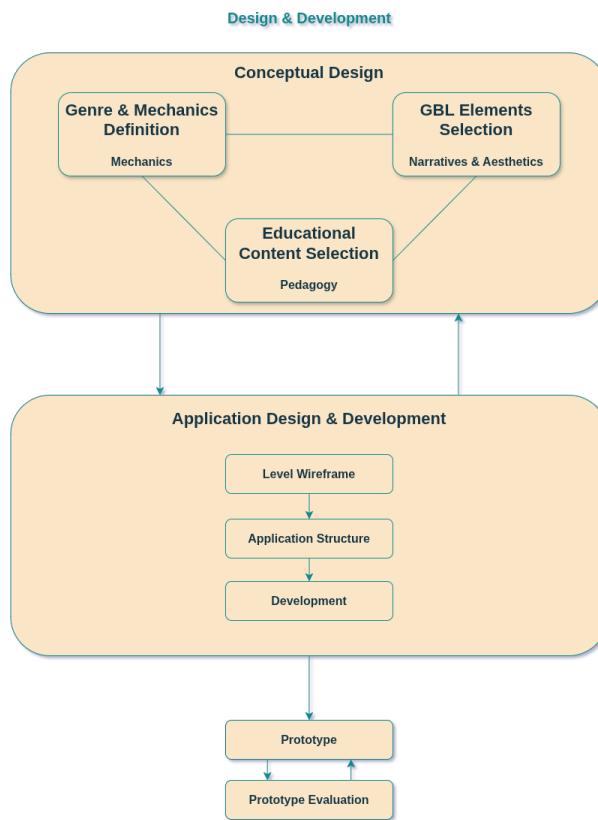


Figure 8.1. Design & Development Process.

The source code of the application has been published on *GitHub*¹ under the *GNU General Public License v3.0* License. The application is available as an *APK*², for installation on Android devices.

The evaluation of the application was carried out using a mix of methods:

1. **Pre-Post Tests:** Evaluation of learning outcomes and knowledge retention
2. **System Usability Scale (SUS) Questionnaire:** Evaluation of the application as an interactive system
3. **Game User Experience Satisfaction Scale (GUESS-18) Questionnaire:** Evaluation of game experience
4. **Focus Group:** qualitative feedback and validation of questionnaire results

¹<https://github.com/StelTheo73/qubity>

²<https://github.com/StelTheo73/qubity/blob/main/release>

8.2 Conclusions

8.2.1 Literature Review Conclusions

From literature review, we concluded the following:

1. The game should belong to the Puzzle genre, as games of this kind have simple rules and mechanisms, they enhance information retention and the majority of educational games - related to quantum computing - belong to this category.
2. In order for the game to be attractive, easy to use and enjoyable, it should include elements and techniques of Game Based Learning, such as:
 - Adaptivity
 - Graceful Failure
 - Incentive System
 - Information Visualization with interactive graphic elements
 - Musical Score
 - Narratives
3. There are few educational mobile applications related to quantum computing and most of them are no longer available.
4. The Quantum Computing theory presented in the game will include concepts such as:
 - Quantum Bits
 - Quantum Registers
 - Quantum Gates: Pauli-X, Pauli-Y, Pauli-Z, Pauli-Z, Hadamard
 - Superposition

8.2.2 Evaluation Conclusions

The research objectives are met, and the game can be considered a successful educational tool, that also provides an enjoyable gaming experience and boosts knowledge retention. Game duration is short, and it can be played on a mobile phone without any additional equipment, so the game is suitable for use in the context of university lecture, as a supplementary educational tool or as a way to enhance engagement and interest for the subject. The results of the questionnaires and the focus group are mutually supportive and confirm our findings, indicating that the game is an easy-to-use, enjoyable, accessible and engaging learning tool, while having simple mechanics and rules. On the other hand, the game has some limitations, such as the limited number of levels, the lack of advanced concepts of quantum computing and the absence of audio and social features.

8.3 Future Work

As discussed in the previous sections, the evaluation process provided valuable feedback that can be used to improve the game in the future. The game should be further expanded to include more levels, more complex puzzles, and additional features to enhance user experience and introduce more advanced concepts of quantum computing. Extra slides could be added to the tutorial level to provide more detailed explanations of the concepts presented in the game. The levels could be grouped into categories based on the concepts they cover, allowing players to focus on specific areas of quantum computing. Audio elements could be added to enhance the gaming experience, such as sound effects for actions and background music. Social features could be implemented that would allow players to share their progress and achievements with friends, or to compete against each other on a leaderboard. Care should be taken to ensure that the game remains educational and not overly competitive. The game could also be translated into other languages to reach a wider audience. In addition, the application could be tested and adapted for use on other platforms, such as iOS and Web, to expand its accessibility, as the current version is only available for Android devices. Finally, the game should be evaluated with a larger sample size to further validate the findings and investigate if it can be used as an effective educational tool in a wider context.

9 Appendix A: Application Screens Presentation

In the previous chapter, we analyzed the conceptual design of our application, defined the development process and evaluation process, and described the development timeline. This chapter focuses on the visual and functional aspects of the game screens. We will present each screen in detail, explaining its purpose and how it contributes to the overall user experience. By understanding the design and functionality of these screens, readers will gain a comprehensive view of how the application operates and how users interact with it.

Home

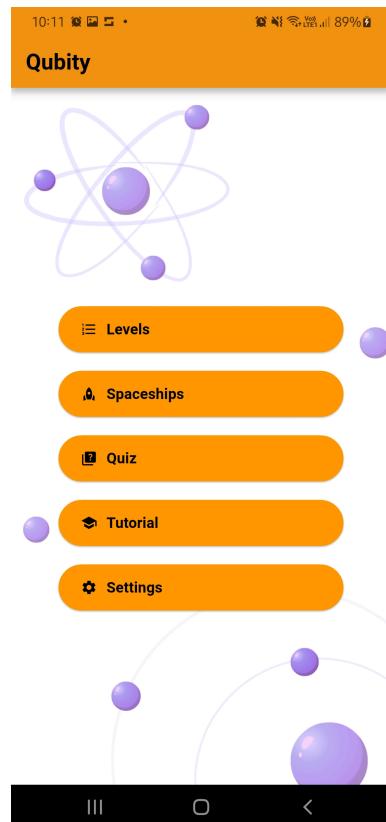


Figure 9.1. Home Screen.

From the app's home screen, the user can access the game levels, available spaceships, the quiz, a tutorial level and game settings.

Tutorial Level

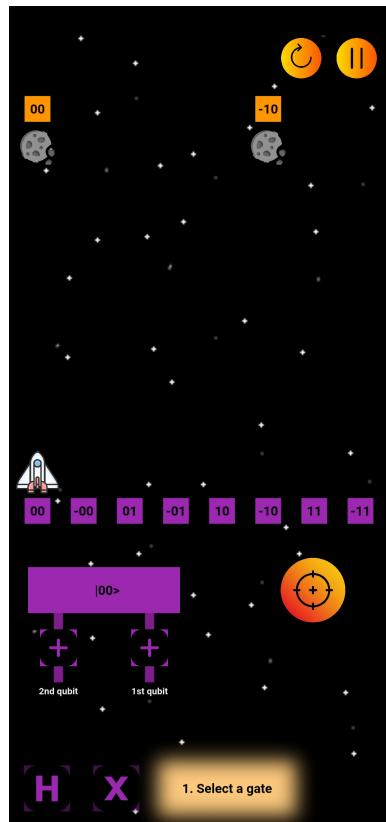


Figure 9.2. Tutorial Level Screen.

This screen loads a tutorial level, for which no score is calculated. First, a few slides are presented with basic quantum computing theory. In particular, the player is introduced to basic theory around qubits, quantum registers and quantum gates, as well as the concept of superposition. The slides consist of short sentences that summarize the theory discussed in chapter 4. Then there are 4 overlays with instructions, which demonstrate to the player how to use the gates to control the spaceship and how to destroy the asteroids.

Level Selection

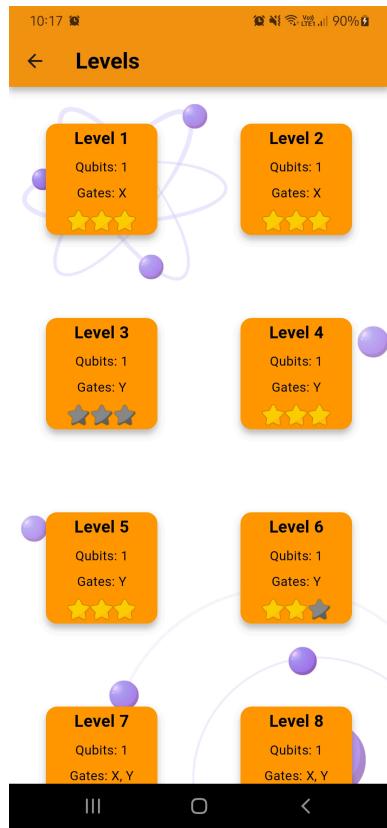


Figure 9.3. Level Selection Screen.

On this screen the player can select any of the available levels. Each level's card shows the number of qubits, the available gates and the score.

Level

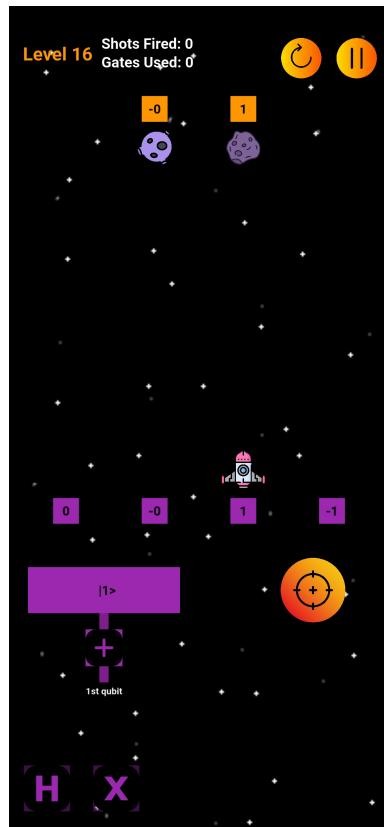


Figure 9.4. Level Screen.

In each level, there are one or more asteroid targets. The player shall move the spaceship under the targets by altering the state of the register. Then, they have to destroy the asteroid by launching missiles. Several levels have more than one solution, but to score maximum points they must use the minimum number of gates and as few missiles as possible. Each level has a different number of possible states, depending on the available gates and the number of qubits.

At the beginning of some levels, there are some slides with theory about the quantum gates available in this level. The first levels are very simple, requiring only 1 use of a gate to put the register into the target state. As the game progresses, the number of gates and combinations increases. In some levels there are gates that do not need to be used. The player needs to use what they have learned to solve the puzzle using the minimum number of gates.

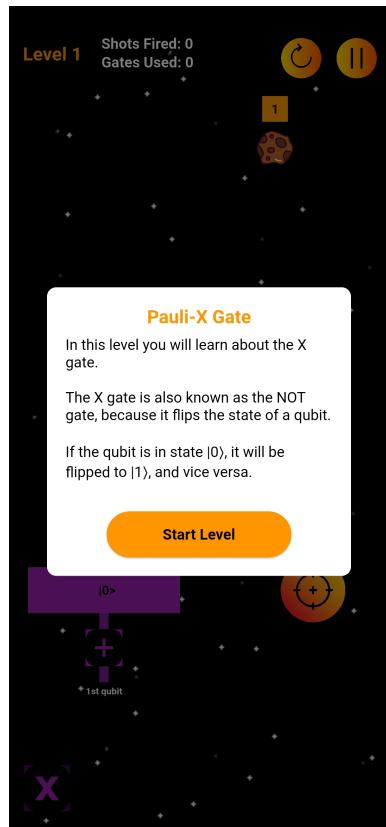


Figure 9.5. Theory Slide.

The first 9 levels introduce the Pauli Gates (X, Y and Z). In level 10, the theory of superposition is reintroduced to increase knowledge retention. Also, Hadamard Gate (H) is introduced. In the next 7 levels, the player is asked to solve the puzzle by combining his previous knowledge of X and H gates.

From level 18, the number of qubits is increased to 2. From this level, no new theory is introduced; the player is just asked to combine their previous knowledge to solve the puzzles. In addition, the level of difficulty increases as the player has to decide which qubit to apply the gate to.

Spaceship Selection



Figure 9.6. Spaceships Selection Screen.

From this screen the player can select one of the available spaceships. The spaceships are decorative in nature, as they all have the same capabilities, but are a reward for the player's progress in the game. Initially only 3 are available, new spaceships are unlocked after completing more levels.

Quiz

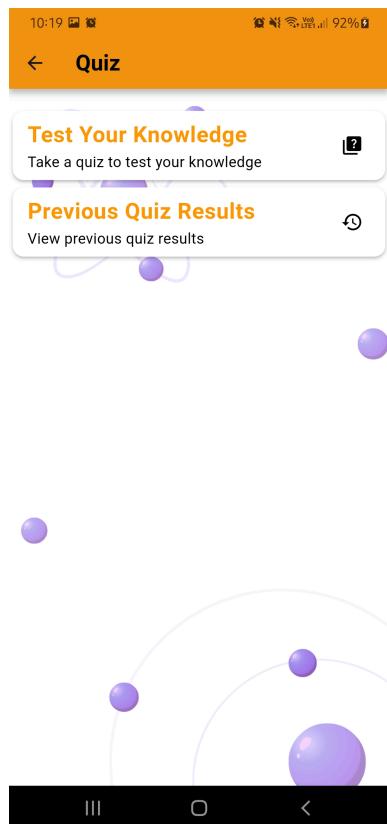


Figure 9.7. Quiz Screen.

The game is accompanied by a 12-question quiz, used for the evaluation process, as described in the previous chapter. This screen gives access to the quiz. The player can take a quiz or view their score from previous attempts.

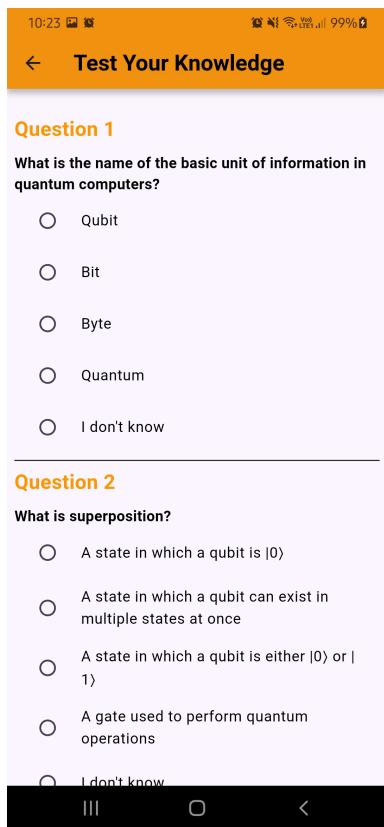


Figure 9.8. Quiz Form Screen.

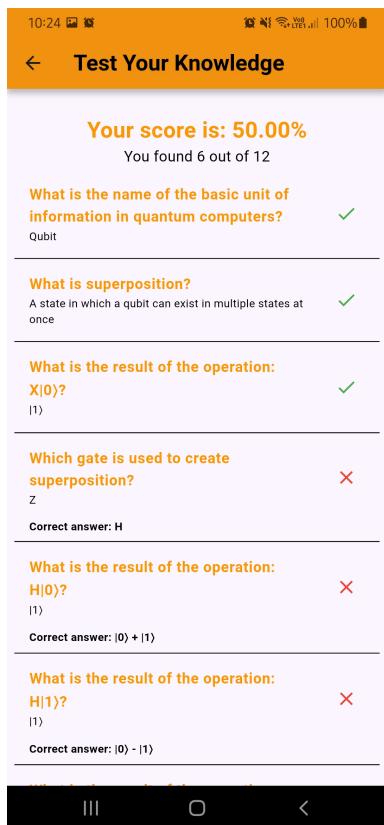


Figure 9.9. Quiz Results Screen.

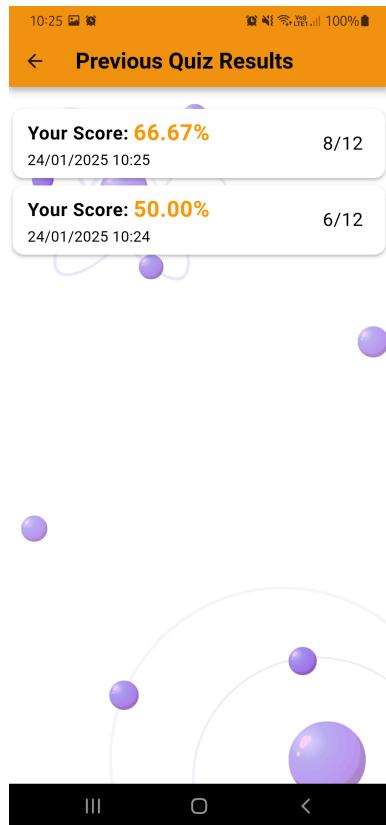


Figure 9.10. Quiz History Screen.

Settings

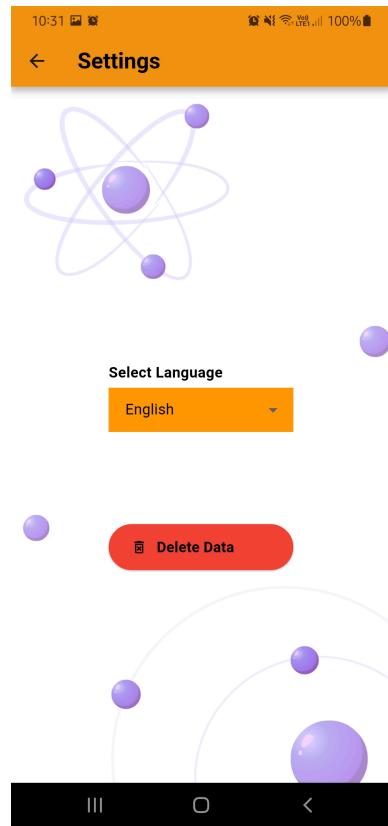


Figure 9.11. Settings Screen.

From this screen, the user can choose between the available languages and delete their progress in the game. Available languages are English and Greek, with the former being the default.

10 Appendix B: Quiz Questions

Question	Answers			
	Qubit	Bit	Bite	Quantum
What is the name of the basic unit of information in quantum computers?				
What is superposition?	A state in which a qubit is $ 0\rangle$	$1\rangle$	A state in which a qubit is either $ 0\rangle$ or $ 1\rangle$	A gate used to perform quantum operations
What is the result of the operation: $X 0\rangle$?	$ 0\rangle$	$1\rangle$	$ 0\rangle + 1\rangle$	$ 0\rangle - 1\rangle$
Which gate is used to create superposition?	X	H	Z	Y
What is the result of the operation: $H 0\rangle$?	$ 0\rangle$	$1\rangle$	$0\rangle + 1\rangle$	$ 0\rangle - 1\rangle$
What is the result of the operation: $H 1\rangle$?	$ 0\rangle$	$ 1\rangle$	$ 0\rangle + 1\rangle$	$0\rangle - 1\rangle$
What is the result of the operation: $-X 1\rangle$?	$ 0\rangle$	$ 1\rangle$	$- 0\rangle$	$- 1\rangle$
What is the result of the operation: $Z 0\rangle$?	$0\rangle$	$ 1\rangle$	$- 0\rangle$	$- 1\rangle$
What is the result of the operation: $Y 1\rangle$?	$- 0\rangle$	$1\rangle$	$- 0\rangle$	$- 1\rangle$
What is the result of the operation: $Z 1\rangle$?	$ 0\rangle$	$ 1\rangle$	$- 0\rangle$	$- 1\rangle$
Which gate would you apply to the left qubit to perform the following computation: $ 00\rangle - 10\rangle - 10\rangle$?	X	H	Z	Y
Which gate would you apply to the left qubit to perform the following computation: $ 00\rangle - 10\rangle \rightarrow 00\rangle + 10\rangle$?	X	H	Z	Y

Figure 10.1. Quiz Questions and Answers.

The correct answers are highlighted with bold text.

11 Appendix C: Questionnaires

SUS Questionnaire

I think that I would like to use this application frequently
I found the application unnecessarily complex
I thought the application was easy to use
I think that I would need the support of a technical person to be able to use this application
I found the various functions in this application well integrated
I thought there was too much inconsistency in this application
I would imagine that most people would learn to use this application very quickly
I found the application very cumbersome to use
I felt very confident using the application
I needed to learn a lot of things before I could get going with this application

Figure 11.1. SUS Questionnaire.

GUESS-18 Questionnaire

Subscale	Statements
Usability / Playability	I find the controls of the game to be straightforward I find the game's interface to be easy to navigate
Narratives	I am captivated by the game's story from the beginning I enjoy the fantasy or story provided by the game
Play Engrossment	I feel detached from the outside world while playing the game I do not care to check events that are happening in the world during the game
Enjoyment	I think the game is fun I feel bored while playing the game (Reverse Code)
Creative Freedom	I feel the game allows me to be imaginative I feel creative while playing the game
Audio Aesthetics	I enjoy the sound effects in the game I feel the game's audio enhances my gaming experience
Personal Gratification	I am very focused on my own performance while playing the game I want to do as well as possible during the game
Social Connectivity	I find the game supports social interaction between players I like to play this game with other players
Visual Aesthetics	I enjoy the game's graphics I think the game is visually appealing

Figure 11.2. GUESS-18 Questionnaire.

Περίληψη

Εισαγωγή

Η παρούσα διπλωματική εργασία διερευνά την αποτελεσματικότητα της μάθησης βασισμένης σε παιχνίδια (Game-Based Learning, GBL), ως εναλλακτική προσέγγιση για την εκμάθηση βασικών εννοιών ενός πολύπλοκου επιστημονικού τομέα, αυτού της κβαντικής υπολογιστικής. Η εργασία αυτή προτείνει ένα παιχνίδι για κινητές συσκευές ως διασκεδαστική, διαδραστική και ελκυστική προσέγγιση για την εκμάθηση θεμελιωδών εννοιών της κβαντικής υπολογιστικής, όπως τα κβαντικά bits, η υπέρθεση, οι κβαντικές πύλες και οι κβαντικοί κατχωρητές. Το παιχνίδι έχει σχεδιαστεί για φοιτητές πανεπιστημίου χωρίς προηγούμενη εμπειρία στην κβαντομηχανική.

Ερευνητικοί Στόχοι

Κύριος στόχος αυτής της διατριβής είναι να σχεδιάσει και να αναπτύξει ένα εκπαιδευτικό παιχνίδι για κινητές συσκευές που διδάσκει τα βασικά στοιχεία της κβαντικής υπολογιστικής. Οι βασικοί στόχοι είναι:

- Δημιουργία ενός απλού και προσιτού παιχνιδιού με ελάχιστους κανόνες και σαφείς στόχους.
- Ανάπτυξη ενός αποτελεσματικού εργαλείου μάθησης για φοιτητές πανεπιστημίου χωρίς προηγούμενη εμπειρία στην κβαντομηχανική.
- Διασφάλιση ότι το παιχνίδι είναι κατάλληλο για σύντομες περιόδους παιχνιδιού, το οποίο περιλαμβάνει και ένα σύντομο τεστ ελέγχου γνώσεων, καθιστώντας το ιδανικό για χρήση ως διδακτικό εργαλείο, στο πλαίσιο πανεπιστημιακών διαλέξεων.

Βιβλιογραφική Ανασκόπηση

Η βιβλιογραφική ανασκόπηση εξετάζει τη θεωρία της μάθησης βασισμένης σε παιχνίδι και υπάρχοντα εκπαιδευτικά παιχνίδια που σχετίζονται με την τριτοβάθμια εκπαίδευση και την κβαντομηχανική. Επισημαίνει τα πλεονεκτήματα της διαδραστικής μάθησης, ιδίως σε αφηρημένα

θέματα όπως η κβαντική πληροφορική. Η ανασκόπηση εντοπίζει επίσης ένα κενό στα υπάρχοντα εκπαιδευτικά παιχνίδια, ενισχύοντας την ανάγκη για ένα νέο παιχνίδι για κινητές συσκευές που θα εστιάζει στις έννοιες της κβαντομηχανικής.

Αρχές Μάθησης Βασισμένης στο Παιχνίδι

Στο παιχνίδι έχουν ενσωματωθεί ορισμένες τεχνικές του GBL. Σύμφωνα με τη βιβλιογραφία, (Plass, Homer, and Kinzer 2015; Shi and Shih 2015), μερικές από τις τεχνικές του GBL είναι:

- **Μηχανισμοί παιχνιδιού:** Οι κανόνες που διέπουν και καθοδηγούν τις ενέργειες των παικτών, καθώς και την αντίδραση του παιχνιδιού σε αυτές. Επίσης καθορίζουν το είδος του παιχνιδιού και τη σύνδεση της εκπαιδευτικής διαδικασίας με το παιχνίδι.
- **Σχεδιασμός Οπτικής Αισθητικής:** Χρήση γραφικών στοιχείων για αναπαράσταση πληροφοριών και παροχή οπτικής ανατροφοδότησης.
- **Μουσική Επένδυση:** Ενσωμάρωση ήχων υποβάθρου, φωνών και απτικής ανατροφοδότησης για να την κατεύθυνση της προσοχής, την ενισχύει συναισθήματα και την παροχή ανατροφοδότησης.
- **Αφηγηματικός Σχεδιασμός:** Χρήση μη γραμμικών αφηγήσεων που εξελίσσονται βάσει των επιλογών του παίκτη, ενισχύοντας τα κίνητρα μέσω διαλόγων, σκηνών και δραστηριοτήτων εντός του παιχνιδιού.
- **Σύστημα Κινήτρων:** Παρακίνηση και ανταμοιβή των παικτών μέσω πόντων, πινάκων κατάταξης, βραβείων και άλλων ανταμοιβών.
- **Προσαρμοστικότητα:** Προσαρμογή των στοιχείων ή της δυσκολίας του παιχνιδιού ώστε να ταιριάζουν με το προφίλ κάθε χρήστη.
- **Ομαλή αποτυχία:** Ενθάρρυνση της ανάληψης ρίσκου και του πειραματισμού.

Βασικές Αρχές Κβαντικής Υπολογιστικής

Για την υποστήριξη του εκπαιδευτικού περιεχομένου του παιχνιδιού, η διατριβή παρέχει μια επισκόπηση των θεμελιωδών εννοιών της κβαντικής υπολογιστικής:

- **Κβαντικά μπιτ (Qubits):** Η βασική μονάδα της κβαντικής πληροφορίας.
- **Υπέρθεση:** Η ικανότητα των qubits να υπάρχουν σε πολλαπλές καταστάσεις ταυτόχρονα.
- **Κβαντικές Πύλες:** Λειτουργίες που μεταβάλλουν την κατάσταση των qubits, επιτρέποντας την εκτέλεση κβαντικών υπολογισμών.

- Κβαντικοί Καταχωρητές: Συλλογές qubits που χρησιμοποιούνται για την αποθήκευση και επεξεργασία κβαντικής πληροφορίας.

Ανάπτυξη Εφαρμογής

Προκειμένου να επιλέξουμε τις κατάλληλες τεχνολογίες για την ανάπτυξη της εφαρμογής, κάναμε μία σύγκριση των διαθέσιμων γλωσσών προγραμματισμού και των frameworks που χρησιμοποιούνται για ανάπτυξη εφαρμογών σε κινητές συσκευές. Αποφασίσαμε να αναπτύξουμε το παιχνίδι με το Flutter, ένα Cross-Platform framework που επιτρέπει την ανάπτυξη εφαρμογών για συσκευές Android και iOS. Για την υλοποίηση των γραφικών και των μηχανισμών του παιχνιδιού χρησιμοποιήθηκε το Flame Game Engine.

Οι πέντε συνιστώσες του σχεδιασμού εκπαιδευτικών παιχνιδιών, όπως ορίζονται από τον Καλμπουρτζή (2018), είναι οι Μηχανισμοί, η Αφηγηματικότητα, η Αισθητική, η Τεχνολογία και η Παιδαγωγική. Έχοντας επιλέξει ήδη τις τεχνολογίες που θα χρησιμοποιήσουμε, ακολουθήσαμε τις υπόλοιπες 4 συνιστώσες κατά το σχεδιασμό και την ανάπτυξη της εφαρμογής.

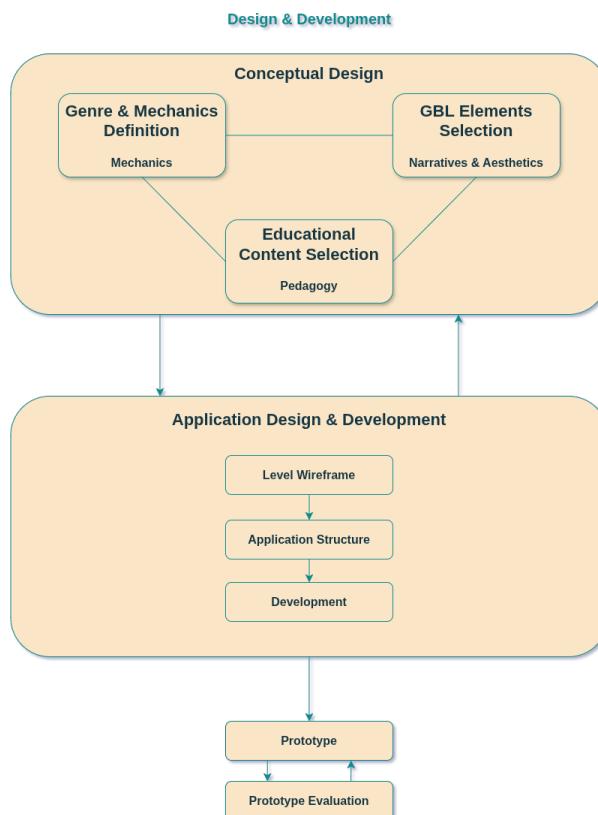


Figure 11.3. Διαδικασία Σχεδιασμού και Ανάπτυξης Πρωτοτύπου.

Η διαδικασία σχεδιασμού και ανάπτυξης, όπως φαίνεται στην παραπάνω εικόνα, αποτελείται από τα εξής στάδια:

1. Εννοιολογικός σχεδιασμός

1. Είδος & Μηχανισμοί Παιχνιδιού

- Ορισμός είδους παιχνιδιού: Puzzle.
- Ορισμός μηχανισμών παιχνιδιού.

2. Εκπαιδευτικό Περιεχόμενο

- Επιλογή των εννοιών της κβαντικής υπολογιστικής που θα παρουσιαστούν μέσω του παιχνιδιού και της σειράς παρουσίασης αυτών.

3. Τεχνικές GBL

- Επιλογή τεχνικών GBL που θα χρησιμοποιηθούν στο παιχνίδι.

2. Δημιουργία Wireframe

- Σχεδιασμός ενός Wireframe το οποίο χρησιμοποιήθηκε ως πρωτότυπο για τη δημιουργία των επιπέδων του παιχνιδιού.

3. Ορισμός Δομής Εφαρμογής

- Ορισμός οθονών και λειτουργικότητας αυτών.
- Σχεδιασμός πλοήγησης μεταξύ οθονών.

4. Δημιουργία Πρωτοτύπου

- Δημιουργία ενός λειτουργικού πρωτοτύπου της εφαρμογής, βάσει των βημάτων 2 έως και 5.

5. Αξιολόγηση & Βελτίωση Πρωτοτύπου

- Αξιολόγηση πρωτοτύπου με δοκιμές χρηστών
- Επανάληψη των βημάτων 4 και 5, μέχρι την επίτευξη ενός ικανοποιητικού αποτελέσματος.

Αξιολόγηση Εφαρμογής

Πρικειμένου να εκτιμηθεί εάν επιτεύχθηκαν οι ερευνητικοί στόχοι, διεξήχθη μία διαδικασία αξιολόγησης με δύο στάδια, την αξιολόγηση της εφαρμογής ως εκπαιδευτικό εργαλείο και την αξιολόγηση της εφαρμογής ως διαδραστικό σύστημα και ως παιχνίδι. Για την αξιολόγηση

της εφαρμογής ως εκπαιδευτικό εργαλείο χρησιμοποιήσαμε την Pre-Post Tests μεθοδολογία, ενώ επαναλάβαμε το Post Test 2 εβδομάδες μετά το αρχικό Test, ώστε να μετρήσουμε και τη διατήρηση της γνώσης (knowledge retention). Για την αξιολόγηση του διαδραστικού συστήματος χρησιμοποιήσαμε το ερωτηματολόγιο SUS και για την αξιολόγηση της εμπειρίας παιχνιδιού το ερωτηματολόγιο GUESS-18. Τέλος, διοργανώσαμε ένα Focus Group, ώστε να συγκεντρώσουμε περισότερα ποιοτικά δεδομένα και να επιβεβαιώσουμε τα ευρήματα των ερωτηματολογίων. Στη διαδικασία αξιολόγησης συμμετείχαν 23 φοιτητές πανεπιστημίου, οι οποίοι είχαν ισχυρό υπόβαθρο στα μαθηματικά.

Για τις ανάγκες των Pre-Post Tests, ενσωματώθηκε στην εφαρμογή ένα Quiz, το οποίο οι παίκτες κλήθηκαν να απαντήσουν 2 φορές, μία φορά πριν παίξουν το παιχνίδι και μία αμέσως μετά. Το Quiz περιλάμβανε 12 ερωτήσεις πολλαπλής επιλογής, οι οποίες σχεδιάστηκαν με βάση τη θεωρία που παρουσιάζεται στο παιχνίδι. Το ίδιο Quiz χρησιμοποιήθηκε και για την αξιολόγηση της διατήρησης της γνώσης, 2 εβδομάδες μετά το αρχικό Quiz. Προκειμένου να μετρηθεί το μαθησιακό αποτέλεσμα χρησιμοποιήθηκε η μετρική *Average Normalized Gain* (g).

Μετά την ολοκλήρωση του Pre-Post Test, οι συμμετέχοντες συμπλήρωσαν τα ερωτηματολόγια SUS και GUESS-18. Μία εβδομάδα μετά, 8 από τους 23 παίκτες συμμετείχαν στο Focus Group. Οι συμμετέχοντες παρείχαν ανατροφοδότηση σεχτικά με τη Γραφική Διεπαφή και την Εμπειρία Χρήστη, τους Μηχανισμούς Παιχνιδιού, τη Δυσκολία και το Σύστημα Βαθμολογίας και Ανταμοιβών. Επιπλέον, έκαναν προτάσεις για τη βελτίωση της εφαρμογής. Στο επαναληπτικό Post Test συμμετείχαν 10 παίκτες.

Αποτελέσματα Αξιολόγησης

Με βάση την ανατροφοδότηση και τα δεδομένα που συλλέχθηκαν από τις δοκιμές Pre-Post, τα ερωτηματολόγια και το Focus Group, μπορούν να εξαχθούν διάφορα συμπεράσματα:

1. Το παιχνίδι είναι ένα αποτελεσματικό εργαλείο μάθησης και διδάσκει με επιτυχία τις βασικές έννοιες της κβαντικής πληροφορικής σε φοιτητές πανεπιστημίου. Η διαφορά μεταξύ των βαθμολογιών των Pre (M.O. 17%) και Post (M.O. 75%) Test και η τιμή του *Average Normalized Gain* (0.7) υποδηλώνουν σημαντική βελτίωση των γνώσεων των παικτών μετά το παιχνίδι. Τα αποτελέσματα του t-test δείχνουν ότι η διαφορά των μέσων όρων είναι στατιστικά σημαντική ($p < 0.001$ για $a = 0.05$).
2. Ο μέσος χρόνος που χρειάστηκαν οι παίκτες για να ολοκληρώσουν το παιχνίδι - εξαιρουμένου του κουίζ - ήταν 18 λεπτά. Αυτό είναι μια καλή ένδειξη ότι το παιχνίδι είναι σύντομο και μπορεί να χρησιμοποιηθεί κατά τη διάρκεια μιας πανεπιστημιακής διάλεξης (ως εκπαιδευτικό εργαλείο) ή όταν ο φοιτητής έχει περιορισμένο χρόνο.
3. Το παιχνίδι είναι ευχάριστο και οι παίκτες βρήκαν τους μηχανισμούς του απλούς. Η πλοήγηση

λειτουργεί καλά και είναι προβλέψιμη.

4. Το επίπεδο δυσκολίας ήταν αποδεκτό, με ορισμένους παίκτες να ζητάνε επίπεδα αυξημένης δυσκολίας. Οι παίκτες συμφώνησαν ότι το παιχνίδι είναι εύκολο και προορίζεται για χρήστες χωρίς εμπειρία γύρω από την κβαντική πληροφορική.
5. Το σύστημα κινήτρων και ανταμοιβών αποδείχθηκε ότι ήταν παρακινητικό και ενθάρρυνε τους παίκτες να βελτιώσουν τις επιδόσεις τους.
6. Το παιχνίδι είχε θετική επίδραση στη διατήρηση της γνώσης, όπως προκύπτει από τα αποτελέσματα της επανάληψης του Post Test. Η μέση βαθμολογία του επαναληπτικού Post Test ήταν 55%, σημαντικά υψηλότερη από τη μέση βαθμολογία στο Pre Test (17%).
7. Η εφαρμογή είναι εύχρηστη, εφόσον κατατάχθηκε ως *Excellent* στην κλίμακα *Bangor* (2009) και ως *A+* στην κλίμακα *Sauro-Lewis* (2011; 2016).
8. Η εμπειρία παιχνιδιού είναι πολύ καλή, σύμφωνα με τα αποτελέσματα του ερωτηματολογίου GUESS-18, τα οποία επιβεβαιώνονται και από την ανατροφοδότηση μέσω του Focus Group.

Συνολικά, η διαδικασία αξιολόγησης ήταν επιτυχής και παρείχε πολύτιμα σχόλια που θα χρησιμοποιηθούν για τη βελτίωση του παιχνιδιού στο μέλλον. Οι ερευνητικοί στόχοι επιτεύχθηκαν και το παιχνίδι μπορεί να θεωρηθεί ένα επιτυχημένο εκπαιδευτικό εργαλείο, το οποίο παρέχει επίσης μια ευχάριστη εμπειρία παιχνιδιού και ενισχύει τη διατήρηση των πληροφοριών. Το παιχνίδι θα πρέπει να επεκταθεί περαιτέρω ώστε να περιλαμβάνει περισσότερα επίπεδα, πιο σύνθετους γρίφους και πρόσθετα χαρακτηριστικά για να βελτιώσει την εμπειρία του χρήστη και να εισάγει πιο προηγμένες έννοιες της κβαντικής πληροφορικής. Το παιχνίδι θα πρέπει επίσης να δοκιμαστεί με μεγαλύτερο μέγεθος δείγματος για την επιβεβαίωση των αποτελεσμάτων.

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