Minor Project Report

on

The Use of Games in Understanding the World of Quantum Computing

by

Ritwik Garg, 20BCP135

Mayur Jivani, 20BCP311D

Under the Guidance of

Dr. Hargeet Kaur

Assistant Professor,

School of Technology

Submitted to

Department of Computer Science and Engineering,

School of Technology,

Pandit Deendayal Energy University

2023

CERTIFICATE

This is to certify that the seminar report entitled "The Use of Games in Understanding the World of Quantum Computing" submitted by Ritwik Garg, has been conducted under the supervision of Dr. Hargeet Kaur, Assistant Professor, and is hereby approved for the partial fulfilment of the requirements for the award of the degree of Bachelor of Engineering in the Department of Computer Science and Engineering at Pandit Deendayal Energy University, Gandhinagar. This work is original and has not been submitted to any other institution for the award of any degree.

Sign:
Dr. Hargeet Kaur,
Assistant Professor,
Department of Computer Science and Engineering,
School of Technology,
Pandit Deendayal Energy University.

Sign:
Dr. Sonam Nahar,
Assistant Professor,
Department of Computer Science and Engineering,
School of Technology,
Pandit Deendayal Energy University.

CERTIFICATE

This is to certify that the seminar report entitled "The Use of Games in Understanding the World of Quantum Computing" submitted by Mayur Jivani, has been conducted under the supervision of Dr. Hargeet Kaur, Assistant Professor, and is hereby approved for the partial fulfilment of the requirements for the award of the degree of Bachelor of Engineering in the Department of Computer Science and Engineering at Pandit Deendayal Energy University, Gandhinagar. This work is original and has not been submitted to any other institution for the award of any degree.

Sign:
Dr. Hargeet Kaur,
Assistant Professor,
Department of Computer Science and Engineering,
School of Technology,
Pandit Deendayal Energy University.

Sign:
Dr. Sonam Nahar,
Assistant Professor,
Department of Computer Science and Engineering,
School of Technology,
Pandit Deendayal Energy University.

Declaration

I hereby declare that the seminar report entitled **The Use of Games in Understanding the World of Quantum Computing** is the result of my own work and has been written by me. This report has not utilised any language model or natural language processing artificial intelligence tools for the creation or generation of content, including the literature survey. The use of any such artificial intelligence-based tools was strictly confined to the polishing of content, spell checking, and grammar correction after the initial draft of the report was completed. No part of this report has been directly sourced from the output of such tools for the final submission. This declaration is to affirm that the work presented in this report is genuinely conducted by me and to the best of my knowledge, it is original.

Ritwik Garg
20BCP135
Department of Computer Science Engineering
School of Technology
Pandit Deendayal Energy University
Gandhinagar

Date: 22/11/2023
Place: PDEU, Gandhinagar

List of Tools Used for the Report with Purpose:
- **ChatGPT:** Correcting Grammar, polishing the text.
- **Google:** Help in writing code.

Declaration

I hereby declare that the seminar report entitled **The Use of Games in Understanding the World of Quantum Computing** is the result of my own work and has been written by me. This report has not utilised any language model or natural language processing artificial intelligence tools for the creation or generation of content, including the literature survey. The use of any such artificial intelligence-based tools was strictly confined to the polishing of content, spell checking, and grammar correction after the initial draft of the report was completed. No part of this report has been directly sourced from the output of such tools for the final submission. This declaration is to affirm that the work presented in this report is genuinely conducted by me and to the best of my knowledge, it is original.

Mayur Jivani
20BCP311D
Department of Computer Science Engineering
School of Technology
Pandit Deendayal Energy University
Gandhinagar

Date: 22/11/2023
Place: PDEU, Gandhinagar

List of Tools Used for the Report with Purpose:
● **ChatGPT:** Correcting Grammar, polishing the text.
● **Google:** Help in writing code.

Acknowledgement

I am deeply grateful to the many individuals and organisations that have played a pivotal role in the completion of my minor project, **The Use of Games in Understanding the World of Quantum Computing**. Foremost, I extend my heartfelt thanks to my mentor, Dr. Hargeet Kaur, Assistant Professor in the Department of Computer Science and Engineering at the School of Technology, Pandit Deendayal Energy University. Her expert guidance, relentless support, and academic rigour have been crucial in shaping the trajectory and substance of my research.

I would like to express my appreciation to the faculty of the Computer Science and Engineering department. Their encouragement and the intellectually stimulating environment they fostered have greatly enhanced the quality of my work. Special thanks are due to Qiskit and IBM for their invaluable resources and tools that were fundamental in exploring quantum computing approaches within the scope of this project. Their contribution has been instrumental in the practical application of quantum computing principles in this research.

I am also thankful for the support and constructive input from my peers and friends. Their insights and shared knowledge have been a source of continuous encouragement and have significantly refined my research. Additionally, my gratitude extends to various online communities and forums that have provided me with an avenue to discuss ideas and gain diverse perspectives. This interaction has enriched my understanding and approach to the complexities of quantum computing in financial optimization.

I must also thank the reviewers and editors who provided constructive criticism and feedback, which greatly improved the quality and clarity of my research. Lastly, I must acknowledge the unwavering support of my family and friends. Their constant encouragement and understanding have been my strength throughout this journey. Their belief in my capabilities and vision has been a source of motivation and resilience. This project is not just my achievement but a testament to the collaborative spirit and collective effort of everyone involved.

Abstract

Even after four decades since its inception, quantum computing remains an esoteric and mysterious subject for the majority. We are rapidly approaching a future where classical computers will be overshadowed by the power of quantum computing. In this imminent quantum-centric world, the demand for a proficient workforce specializing in quantum systems development and maintenance is evident. This project is motivated by the ambition to make quantum computing approachable and engaging, using interactive games as a tool.

Games serve as powerful educational tools by providing an immersive and interactive learning environment. Whether in the context of mathematics, science, or other disciplines, games have the unique ability to make complex concepts more accessible and enjoyable. They engage learners through challenges, problem-solving, and strategic thinking, fostering a deeper understanding of abstract ideas. Furthermore, games encourage active participation, collaboration, and the application of knowledge in practical scenarios. In alignment with these principles, our primary objective is to bridge the quantum computing knowledge gap by delivering a hands-on and enjoyable learning experience.

To materialize this vision, we have developed an innovative card game that serves as a powerful educational tool. This game is designed to elucidate intricate quantum concepts such as quantum gates, quantum superposition, quantum measurement, quantum entanglement, and quantum teleportation in an engaging and accessible manner. By gamifying the learning process, we aim to demystify these complex quantum principles and make them comprehensible for a broader audience, from students and enthusiasts to future quantum computing specialists. The objective is to empower individuals with the knowledge needed to navigate the emerging world of quantum computing with confidence and enthusiasm.

Table of Content

List of Figures

1. Introduction

Quantum computing, a cutting-edge field at the intersection of physics and computer science, represents a paradigm shift in how we process information. Unlike classical computers that rely on bits, which can exist in either a 0 or 1 state, quantum computers leverage quantum bits, or qubits, which can exist in multiple states simultaneously due to the principles of superposition and entanglement. This unique ability allows quantum computers to perform certain computations exponentially faster than their classical counterparts, promising breakthroughs in areas such as cryptography, optimization, and simulation.

The conceptual roots of quantum computing trace back to physicist Richard Feynman's proposal in the early 1980s to simulate quantum systems efficiently. The pivotal developments came in the late 1990s with the introduction of ground-breaking algorithms by Peter Shor and Lov Grover. Shor's algorithm demonstrated the potential for quantum computers to factor large numbers exponentially faster than classical algorithms, posing a threat to traditional cryptographic methods. Grover's algorithm showcased quantum speedup for database search problems, further highlighting the transformative capabilities of quantum computation.

Today, quantum computing is not merely a theoretical pursuit; it has tangible implications for solving complex problems that exceed the capabilities of classical computers. From drug discovery and materials science to optimization challenges in logistics and finance, quantum computing holds the promise of unlocking solutions to problems previously deemed insurmountable. Companies and researchers worldwide are actively exploring the practical applications of quantum computing, ushering in an era of transformative technological advancements.

Quantum computing, grounded in the intricate principles of quantum mechanics, presents a unique educational challenge due to its abstract and counterintuitive nature. As the demand for quantum literacy grows, traditional instructional methods face limitations in effectively conveying the complexities of quantum phenomena, prompting a need for innovative approaches that bridge the gap between theory and practical understanding.

This report embarks on an exploration of a distinctive avenue in quantum education – the integration of games as a dynamic and immersive tool for understanding the world of quantum computing. Quantum concepts, such as superposition, entanglement, and quantum parallelism, often elude traditional teaching methods, requiring a shift towards interactive and engaging platforms. Games, with their capacity to provide hands-on experiences and foster intuitive learning, emerge as a promising solution to address the challenges inherent in quantum education.

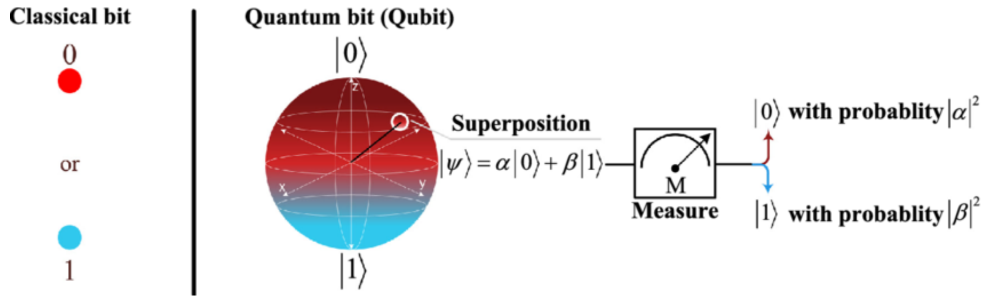

Fig 1. A classical bit vs. a quantum bit (qubit)

At the heart of this report lies a novel educational initiative that leverages the dynamic world of gaming to unravel the mysteries of quantum computing. ‘**QNO!**’ is a quantum-inspired card game that draws inspiration from the renowned UNO flip, reimagining its mechanics to serve as an engaging and educational tool. 'QNO!' embarks on a quantum gaming odyssey, seamlessly integrating the principles of quantum computing into its gameplay, transforming abstract concepts into tangible, interactive experiences.

In the following sections, we will delve into the design and dynamics of 'QNO!,' exploring how it encapsulates quantum gates, superposition, measurement, entanglement, and teleportation within its gameplay.

2. Literature Review

The integration of games as educational tools to elucidate quantum computing concepts has gained prominence in recent years. Researchers and educators recognize the unique challenges posed by the abstract nature of quantum mechanics and the need for innovative approaches to enhance quantum literacy. Game-based learning stands out as a dynamic method capable of providing interactive and immersive experiences, facilitating a deeper understanding of quantum phenomena.

The concept of quantum computing ushered in an era of ideas relating to quantum games and thought experiments. These games and thought experiments aimed to exploit fundamental quantum concepts to explain how quantum systems behave differently from classical systems and how quantum effects can be used to create a monopoly in certain games.

One such game is described by S. C. Benjamin and P. M Hayden [1] in their work titled ‘Multi-Player Quantum Games’. In this article, they discuss the concept of Prisoner's Dilemma in the context of quantum game theory. In classical game theory, the Prisoner's Dilemma is a well-known scenario in which two rational individuals acting in their own self-interest make decisions that result in a suboptimal outcome for both. Each prisoner must choose whether to cooperate with their partner or to betray them. The payoff table for this scenario typically shows that the best outcome for an individual occurs when they betray their partner while their partner remains silent. However, if both prisoners betray each other, they both receive a lower payoff compared to if they both remained silent. This results in a dilemma where both prisoners have an incentive to betray each other, leading to a suboptimal outcome for both.

The article expands upon this classic scenario by introducing the concept of quantum game theory. It explains that when the players are allowed to use quantum strategies, new forms of equilibrium can emerge. In the quantum version of the Prisoner's Dilemma, the players can escape the suboptimal outcome by playing cooperatively with the knowledge that no player can successfully betray the others. This is facilitated by utilizing quantum entanglement, which acts as a contract preventing players from defecting against one another. Through quantum entanglement, the prisoners can arrange their strategy so that they always make the same choice. If they agree to cooperate, their entangled qubits will be correlated to ensure both choose cooperation. Similarly, if they decide to betray, their entangled qubits will correlate to ensure both choose betrayal. Therefore, in the quantum version of the game, the players can achieve a more favourable outcome compared to their classical counterparts and can overcome the classical dilemma.

Another interesting thought experiment comes from the paper titled ‘Quantum Strategies’ by David A. Meyer [2]. The game involves 2 players ‘P’ and ‘Q’. A penny is placed in an opaque box initially with 'head up' position. Neither player can see the coin's current state. Player Q starts the game and can decide to flip the coin or not, without P seeing. Next, Player P makes a similar decision to flip or not, without Q seeing. Lastly, Player Q gets another turn to decide to flip or not, again without P seeing. After these three rounds of decisions, the coin is observed. If the coin is now 'tail up', Player P wins. If the coin remains 'head up', Player Q wins.

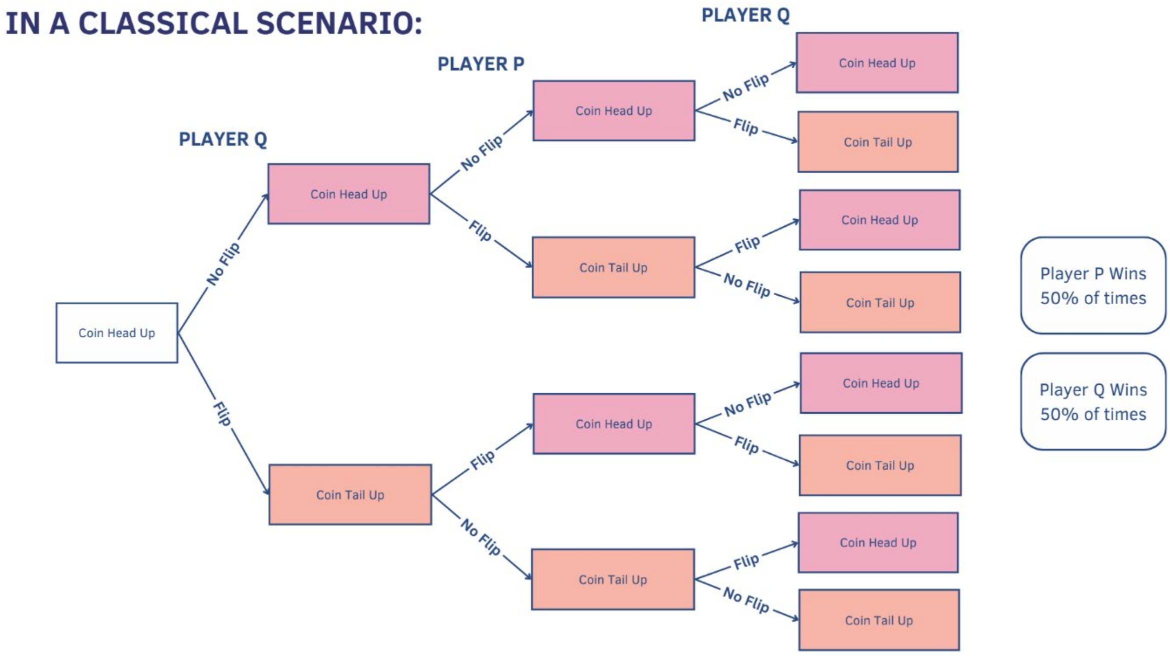

Fig 2. The Penny Flip Game in a classical scenario

In a classical scenario, both players, 'P' and 'Q', have an equal probability of winning the game. However, in a quantum scenario, there is a case where player 'Q' wins 100% of the games. This scenario involves assuming the coin as a quantum coin which can be subjected to quantum gates. In such a case, the player 'Q' can exploit the effect of quantum gates to gain a monopoly over the game. During player Q's turn, he can choose to apply a Hadamard gate on the coin, putting the coin in a state of superposition. In such a state the coin can be considered to be equally mixed state of 'heads up' and 'tails up' simultaneously. Consequently, now any action that player 'P' takes, to flip the coin or not, will have no effect on the superposition state, hence giving player 'Q' complete control over the game's outcome.

IN A QUANTUM SCENARIO:

There is a scenario where Player Q wins **100%** of the games. This is when player Q uses the Hadamard gate at the first move, thus putting the coin in a state of superposition.

Suppose 'Head Up' : $|0\rangle = \begin{vmatrix} 1 \\ 0 \end{vmatrix}$ Suppose 'Tail Up' : $|1\rangle = \begin{vmatrix} 0 \\ 1 \end{vmatrix}$ $H = \frac{1}{\sqrt{2}} \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix}$

Initially Coin is placed 'Head Up' = $|0\rangle$

$$|\Psi 1\rangle = H|0\rangle = \frac{1}{\sqrt{2}} \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \end{vmatrix} = \frac{1}{\sqrt{2}} \begin{vmatrix} 1 \\ 1 \end{vmatrix} = (|0\rangle + |1\rangle) / \sqrt{2}$$

Now whatever action that Player A performs on the coin, will have no effect on the superposition.

If Player B applies the Hadamard transformation again, then they get the original state back as the end result.

$$|\Psi 2\rangle = H|\Psi 1\rangle = \frac{1}{\sqrt{2}} \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix} \frac{1}{\sqrt{2}} \begin{vmatrix} 1 \\ 1 \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \end{vmatrix} = |0\rangle$$

HENCE, THE COIN IS ALWAYS 'HEAD UP,' AND PLAYER Q WINS THE GAME 100% OF THE TIME.

Fig 3. The Penny Flip Game in a quantum scenario

This simple yet insightful experiment demonstrates how quantum techniques, such as superposition and quantum gates, can be strategically employed in game theory to alter classical outcomes, offering 'Q' a distinct advantage. It underscores the fundamental distinction between quantum and classical systems, showcasing the unique ways in which quantum properties can be harnessed for strategic purposes in simple gaming scenarios.

Justin Weisz et.al [3] proposed an intuitive board game as a medium to introduce quantum computing to students and enthusiasts. In their work titled ‘Entanglion: A Board Game for Teaching the Principles of Quantum Computing’, they introduce a new board game concept called ‘Entanglion’. The game focuses on the thought process of computational thinking, which involves problem-solving through breaking down problems into smaller parts, thinking about solutions as sequences of ordered steps, and using abstraction to make generalizations, in alignment with how computers work. The game's objective is to train the first generation of "quantum native" programmers who can think in a "quantum computationally" way and devise new quantum algorithms to solve real-world problems.

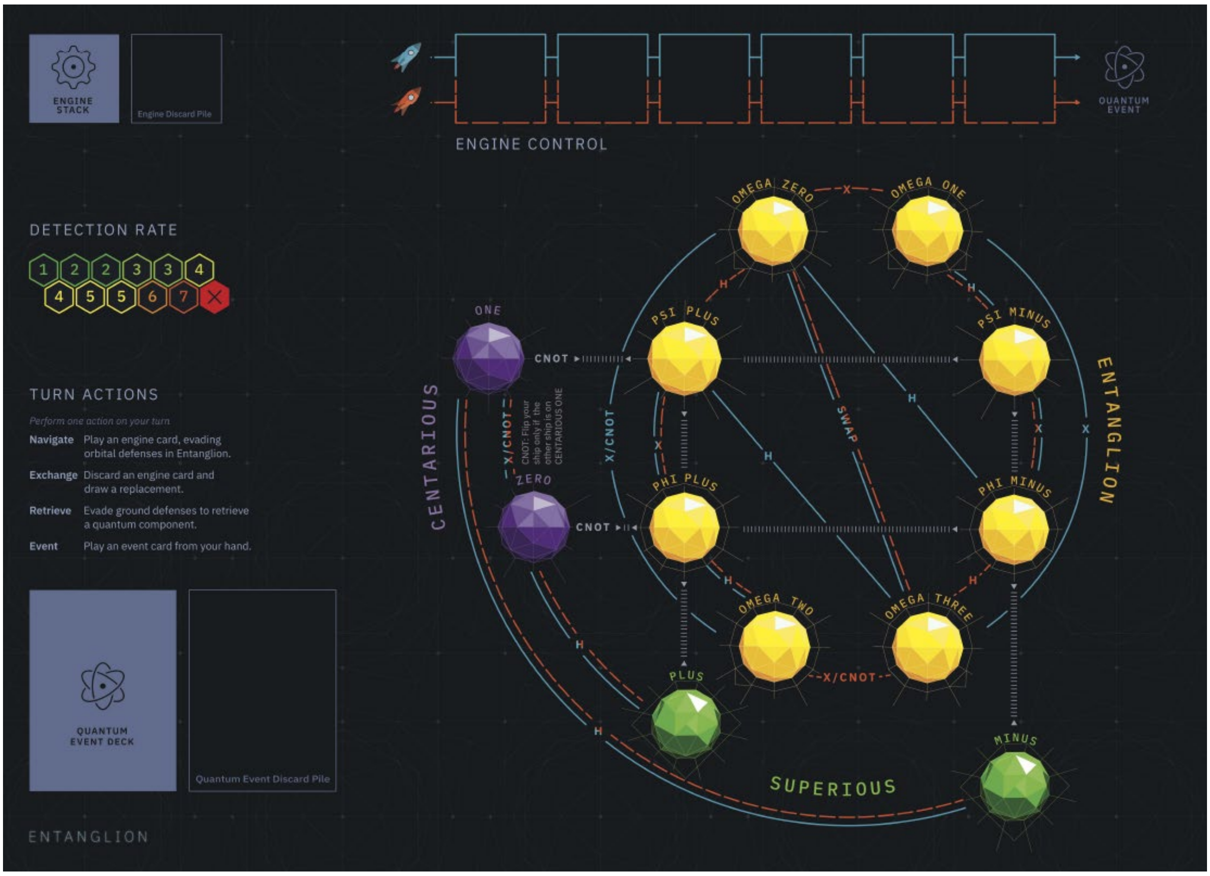

Fig 4. Entanglion, the board game

Entanglion is a cooperative board game that simulates a 2-qubit quantum system. It introduces players to quantum computing concepts such as qubits, quantum states, quantum gates, superposition, entanglement, measurement, and error, as well as the hardware and software components of a quantum computer. The game aims to teach players about the underlying linear algebraic math and the hardware implementation of quantum computers in an enjoyable and unique way.

‘Entangle Me!’ is an interactive and hands-on game created by Andrea L. and Wolfgang D. [4] Through the medium of a game, they illustrate the principles of quantum mechanics to students using a qubit (or spin-first) approach, allowing them to experience and discover its puzzling features first-hand. The game involves students taking on the roles of both particles and scientists, allowing them to simulate a real laboratory and internalize the non-classical features and strange properties of the quantum world. The game introduces a unique physical aspect which requires students to imagine their bodies as single qubit systems, with the position of their legs representing the computational basis states $|0\rangle$, $|1\rangle$ and the positions of their hands representing the x-basis $|+\rangle$ and $|-\rangle$. Similarly, the interaction between 2 students is used to represent an entanglement state composed of 2 qubits. Overall, the game was successful in illustrating the basic principles of quantum mechanics, allowing students to directly experience these principles while acting and working like real scientists, and enhancing their understanding and significance of quantum systems.

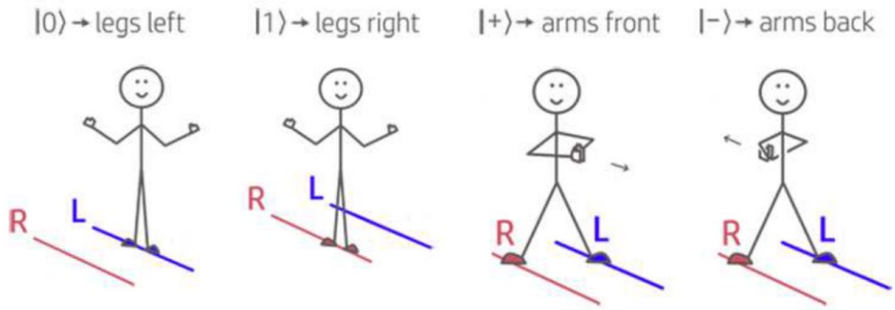

Fig 5. Entangle Me!

3. Methodology

The primary objective of this project is to develop an innovative and engaging card game, 'QNO!', that serves as an effective educational tool for understanding fundamental quantum computing concepts. The overarching goal is to bridge the knowledge gap in quantum computing by providing a hands-on and enjoyable learning experience. 'QNO!' aims to demystify complex quantum principles, including quantum gates, superposition, measurement, entanglement, and teleportation, making them accessible to a diverse audience. Through this game, we seek to foster a deeper understanding of quantum phenomena, encourage active participation in learning, and empower individuals with the knowledge needed to navigate the emerging world of quantum computing with confidence and enthusiasm.

3.1 Objectives

The game was developed while keeping the following objectives in mind:

- Incorporate Quantum Concepts: Integrate quantum concepts seamlessly into the game design, ensuring that each card and game mechanic authentically represents fundamental principles such as quantum gates, superposition, measurement, entanglement, and teleportation.
- Align with Educational Frameworks: Design 'QNO!' to align with established quantum computing curricula, ensuring that the game serves as a supplementary educational resource that complements theoretical learning.
- Promote Interactive Learning: Create an interactive learning experience where players actively engage with and apply quantum principles during gameplay, fostering a deeper and more intuitive understanding.
- Iterative Prototyping: Implement an iterative prototyping process, involving playtesting and feedback loops to refine the game's mechanics, ensuring alignment with educational objectives and enhancing overall player experience.
- Evaluate Educational Impact: Conduct thorough evaluations to assess the educational impact of 'QNO!' by analysing quantitative and qualitative feedback, measuring improvements in quantum knowledge, and identifying areas for potential enhancements in future iterations.

3.2 Game Design Principles

In crafting 'QNO!', a set of foundational game design principles were meticulously considered. These principles serve as the guiding framework for the integration of quantum elements into the game, ensuring both educational efficacy and an enjoyable player experience.

- Authentic Representation of Quantum Concepts: A paramount focus was placed on meticulously aligning the game mechanics to authentically represent quantum concepts and phenomena. 'QNO!' strives to offer a precise visual portrayal of the intricate effects associated with quantum gates, measurement, superposition, entanglement, and teleportation.

- Seamless Integration with UNO Flip Dynamics: UNO Flip was chosen as a reference model since its successful dynamic provides a familiar structure for players, making the transition to quantum concepts smoother and more intuitive.
- Interactivity and Replayability: We chose a card game based on UNO Flip because it allows multiple players to join in, making it ideal for educating several people at once. Games like UNO Flip are also great for learning because they combine skill and luck, making them enjoyable to play over and over again.
- Reinforcement of Quantum Vocabulary: Key quantum terms and symbols are strategically integrated into the game, promoting familiarity and reinforcing the quantum vocabulary essential for understanding more advanced quantum computing concepts.

3.3 Targeted Learnings

Through the game we attempt to explain the following learning objectives:

1. Single qubit states
    - The computational basis states of qubits i.e. $|0\rangle$ and $|1\rangle$.
    - Representation of the basis states on the Bloch Sphere.
    - Relative phase of qubits.
2. Single qubit quantum gates
    - Effect of Pauli-X, Pauli-Y and Pauli-Z gates on single qubit states.
3. Superposition
    - Difference between basis states and superposition states.
    - Result of the collapse of a superposition.
4. Measurement
    - Effect of measurement on collapsing a quantum system to its basis states.
    - Non - deterministic nature of quantum measurement.
5. Entanglement
    - Behaviour of entangled particles and the measurement of entangled states.
6. Teleportation
    - The phenomena of quantum teleportation.

In addition to this, the game is designed so that players can intuitively learn the effects of different cards and decipher favourable outcomes from unfavourable ones. Thus the game promotes computational thinking, mimicking the process used by scientists while developing quantum systems.

4. Implementation Details

In this section, we explain how the game is played, while going over the game mechanics and components. We will first introduce the objective of the game, followed by an introduction to the effects of each card while simultaneously explaining the quantum computing concepts they were designed to mimic.

4.1 Game Objective and Components

'QNO!,' short for 'Quantum UNO!,' is a competitive card game designed for 2-4 players. Following the familiar format of traditional UNO, players receive a random hand of cards at the outset. The primary goal is to strategically discard all the cards in hand, with the first player achieving this declared the winner. The game unfolds until only one player retains cards, adding a competitive edge and encouraging strategic play.

The game features an extensive deck comprising 108 cards, each intricately designed to represent a quantum computing concept or phenomenon. These cards are unique in that each has two faces: one showcasing a light side colour, and the other revealing a dark side colour. The cards are categorized into two main types:

1. Normal Cards: Each normal card serves as a representation of a quantum system, embodying five distinct physical observables. In simpler terms, these cards are characterized by the following properties:

    - State: Reflects the computational basis of a qubit, distinguishing between $|0\rangle$ and $|1\rangle$ states.
    - Light Side Colour: Indicated by vibrant colours such as 'red,' 'blue,' 'green,' and 'yellow.'
    - Light Side Number: Marked by numbers ranging from 0 to 9, adding a numerical dimension to the card.
    - Dark Side Colour: Exhibits colours such as 'orange,' 'teal,' 'purple,' and 'pink' on the dark side of the card.
    - Dark Side Number: Features numbers ranging from 0 to 9 on the dark side, contributing to the card's comprehensive representation.

    Note: *The light side colour/dark side colour of a card may be black in the case of a special card, introducing a unique and visually distinctive element to the game.*

2. Special Cards: Special cards in the deck emulate specific quantum phenomena, introducing an extra layer of intrigue to the game. This category further breaks down into two distinctive types:

    - Coloured Special Cards: These special cards feature light or dark colours on their faces, contributing to the visual richness of the game. Included in this subset are cards like 'Pauli-X,' 'Pauli-Z,' 'Pauli-Y,' and 'Teleportation.' Each of these cards carries unique effects and game-altering dynamics.
    - Black Coloured Special Cards: Distinguished by an exclusive black colour, these special cards play a pivotal role in the game's strategy and unpredictability. The 'Superposition,' 'Colour Superposition,' 'Measurement,'

and 'Entanglement' cards fall into this category, each offering distinctive functionalities that add depth and complexity to the gaming experience.

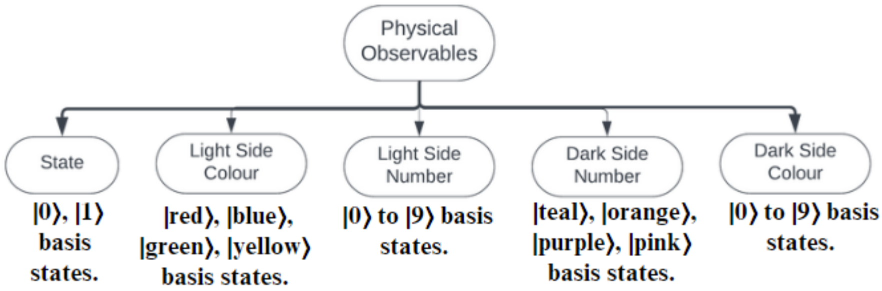

Fig 6. Physical properties of each card

Fig 7. Normal cards showing the different card colours, states and numbers

4.2 <u>Game Initialisation</u>

At the start of the game, the deck of 108 cards is divided into 3 categories:

1. <u>Draw Pile:</u> The entirety of the initial deck, comprising 108 cards, constitutes the 'Draw Pile.' This pile serves as the primary reservoir from which cards are dispensed to each player at the outset and subsequently throughout the game as needed. Initially, the draw pile is arranged so that all cards display their dark-coloured faces (in shades of orange, teal, purple, and pink) upwards.
2. <u>Cards in the Player’s Hand:</u> In the typical initiation of a QNO! game, every player is dealt a hand comprising 7 cards. Ensuring fairness, the deck undergoes thorough shuffling, and the cards are distributed with their dark-coloured faces facing upwards. After receiving their cards, players hold them in a way that only the dark-coloured card faces are visible to their opponents, maintaining an element of secrecy and strategic planning.
3. <u>Discard Pile:</u> Once all players have received their hands, the topmost card from the Draw Pile is uncovered, displaying its light-coloured face. This card becomes the inaugural card in the 'Discard Pile.' Subsequently, players proceed to discard cards from their hands onto the Draw Pile, adhering to the established rules of the game. This initial move sets the tone for the evolving dynamics of the Discard Pile throughout the game.

4.3 Game Rules

The game obeys the following rules:

Turn Order:
Players engage in turns, following a clockwise sequence, adding a strategic layer to the gameplay. However, this order may be changed by the effect of the Pauli-Y and Pauli-Z cards.

Card Play:
To advance in QNO!, players strategically play cards matching either the colour, number, or special effect of the top card on the discard pile. This dynamic element requires players to make calculated decisions based on the current game state. One thing to note here is that the last card played CANNOT be a special card, it must be a normal card.

Special Quantum Element Cards:

- Superposition: The Superposition card allows a player to create a superposition, introducing an element of uncertainty to be resolved by the next player.
- Measurement: The Measurement card serves a dual purpose. It can either collapse an existing superposition or unveil the mystery of the top card in the draw pile, offering players strategic choices that echo the uncertainty of quantum states.
- Pauli X, Pauli Z, Pauli Y: These special cards bring quantum alterations to the game. Mimicking their quantum counterparts, each introduces unique and game-altering effects, adding complexity and excitement.
- Teleportation: The teleportation card empowers a player to exchange a card from an opponent's hand, introducing an element of surprise and strategic manoeuvring.
- Colour Superposition: The Colour Superposition card randomly changes the current colour, challenging the next player to adapt to the unexpected shift, simulating the probabilistic nature of quantum events.
- Entanglement: True to its quantum inspiration, the Entanglement card links two cards, creating a ripple effect for subsequent players. It introduces an intriguing dynamic, mirroring the correlated behaviour observed in entangled quantum particles.

We will have a more in depth look at the effect of each card, in the next section of the report.

Winning:
Victory in QNO! is claimed by the first player to successfully play all their cards, triumphantly declaring "QNO!". In the event of draw pile depletion, the discard pile is reshuffled excluding the card at the top and the bottom of the discard pile, to form the new draw pile.

4.4 Game Mechanics and Special Card Effects

In this section we explain the fundamental quantum computing concepts modelled in QNO!.

Qubits and Quantum States

Qubits are the fundamental computing blocks of quantum computers. Unlike a classical bit, a qubit can be in a combined state of 0 and 1, represented as $|0\rangle$ and $|1\rangle$. These are known as the computational basis states. When qubits are in the states $|0\rangle$ and $|1\rangle$, they are considered to be in the 'classical state' since $|0\rangle$ is analogous to a classical 0 bit and $|1\rangle$ is analogous to a classical 1 bit. Qubits can also be in a state of superposition or a state of entanglement.

In QNO!, the state of a qubit is represented through the Bloch Sphere which is drawn on both faces of the cards. A Bloch sphere is a geometrically accurate 3D representation of the state of a qubit. The card face with the light side colour represents the |0⟩ base state. This is represented by an arrow pointing towards the north pole of the Bloch Sphere. Likewise, the card face with the dark side colour represents the |1⟩ base state. This is represented by an arrow pointing towards the south pole of the Bloch Sphere.

By virtue of the Bloch Sphere, players can visually infer how a qubit is represented and its different states.

Fig 8. Card faces showing the |0⟩ and |1⟩ states

Quantum Gates

Quantum gates are unitary operations that can be applied on qubits to manipulate them. Similar to gates found in classical computing, quantum gates alter the state of a qubit, however, unlike classical gates, the effects of the quantum gates are reversible. These gates are represented by matrices and the application of gates implies a matrix transformation. For example, the Hadamard gate (H) can be used to put a qubit in a classical state into an equal superposition state of the classical states.

In the game, 3 single qubit quantum gates have been introduced – Pauli-X gate, Pauli-Y gate and the Pauli-Z gate. The functioning of each of these gates has been explained below:

- <u>Pauli-X gate</u>:

  The Pauli-X gate is a single qubit quantum that is analogous to a NOT gate in classical computing. It performs a 'flip' operation by converting a qubit initially in |0⟩ state to a |1⟩ state and vice versa.

  Mathematically, if |ψ⟩ is the initial state of the qubit, applying the Pauli X gate transforms it as follows:

  $X|\psi\rangle = |1\rangle$ when $|\psi\rangle = |0\rangle$, and $X|\psi\rangle = |0\rangle$ when $|\psi\rangle = |1\rangle$.

  In the game, the effect of this gate is shown by 'flipping' the cards faces from the |0⟩ face to the |1⟩ face and vice versa. This provides a visual cue to the players about the workings of a Pauli-X gate by representing a physical flip of the card faces, showing the transition between the |0⟩ and |1⟩ states.

- Pauli-Z gate:
  In quantum computing, the Pauli-Z gate is a fundamental quantum gate that introduces a phase flip in the quantum state. Specifically, it changes the sign (or phase) of the state $|1\rangle$, leaving the $|0\rangle$ state unaffected.

  Mathematically, if $|\psi\rangle$ is the initial state of the qubit, applying the Pauli Z gate transforms it as follows:

  $Z|\psi\rangle = |0\rangle$ when $|\psi\rangle = |0\rangle$, and $Z|\psi\rangle = -|1\rangle$ when $|\psi\rangle = |1\rangle$.

  In the game, the 'phase' or rotation of a qubit has been abstracted as the rotation of player turns, implying that a change in the phase of a qubit, changes the rotation of player turns. Hence when the Pauli-Z card is played, the direction of play is reversed. So for example, if the initial direction of play was clockwise, after the Pauli-Z card is played, the new direction of play becomes anti-clockwise and vice versa.

- Pauli-Y gate:
  The Pauli-Y gate introduces both a bit flip and a phase flip to a quantum state. In essence, it combines the effects of the Pauli-X and Pauli-Z gates.

  Mathematically, if $|\psi\rangle$ is the initial state of the qubit, applying the Pauli Y gate transforms it as follows:

  $Y|\psi\rangle = i|1\rangle$ when $|\psi\rangle = |0\rangle$, and $Y|\psi\rangle = -i|0\rangle$ when $|\psi\rangle = |1\rangle$.
  The Pauli-Y card in QNO! mirrors its quantum counterpart's dual effect. When played, the Pauli-Y card in the game not only reverses the direction of play, similar to the Pauli-Z card, but it also flips the card faces. Hence it portrays the fact that the Pauli-Y card combines the effects of the Pauli-X and Pauli-Z cards.

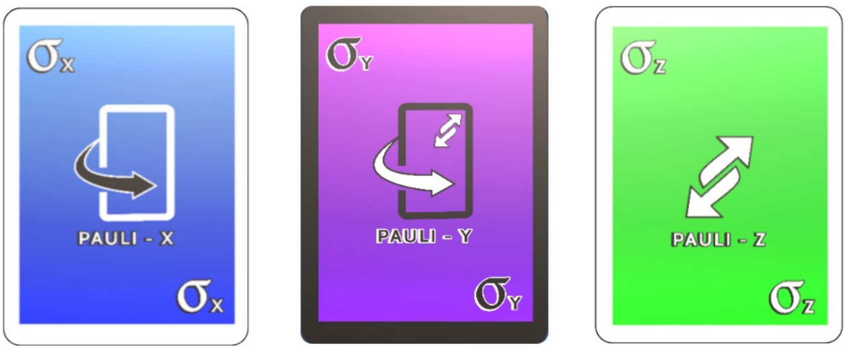

Fig 9. The Pauli-X, Y and Z cards respectively

Superposition
Till now we have seen that a qubit can exist in the classical states of $|0\rangle$ and $|1\rangle$. However, the unique nature of qubits also allows them to be in a combination of these classical states. This property of a qubit is known as superposition. An arbitrary qubit is represented by,

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $|\Psi\rangle$ represents an arbitrary quantum state, $|0\rangle$ and $|1\rangle$ represents the computational basis states and α, β are complex numbers which represent the probability amplitude associated with the $|0\rangle$ and $|1\rangle$ states respectively.

Modelled after quantum superposition, the Superposition card in QNO! introduces a captivating twist to the game. When played, this card places the state, colour, and number of the card into a superposition. Since the game can only continue in the basis state of each physical observable, the superposition card halts the normal functioning of the game. The next player is then faced with a decision: either play another Superposition card to collapse the superposition into the original state, or play a Measurement card to reveal the top card from the draw pile, causing the superposition to collapse randomly. If the next player lacks both of the two cards, they must continue drawing cards from the draw pile until they obtain one of these cards.

Another implementation of quantum superposition is in the form of the Colour Superposition card. This card only places the colour of a card into superposition. Subsequently, the superposition is measured as well, resulting in a random but probabilistic collapse of the superposition into its constituent basis states. Unlike traditional UNO where a colour change card gives the player the choice of deciding the new playing colour, the colour superposition randomly collapses to one of the basis colour states, further showing the non-deterministic nature of quantum measurement.

Fig 10. The Superposition and Colour Superposition cards

This game mechanic mirrors the probabilistic nature of quantum superposition. Players experience the challenge of navigating the game's uncertainty, akin to the unpredictable behaviour of quantum systems in superposition. By incorporating this quantum concept into the gameplay, the Superposition card serves as both an element of reward and punishment into the game and an educational tool, allowing players to interact with the abstract idea of superposition in a tangible and entertaining way.

Measurement

In quantum mechanics, measurement is a fundamental process that reveals the state of a quantum system. When a measurement is performed on a quantum system, the system's state collapses from a superposition of possible states to a definite state. This collapse is inherently probabilistic, with the outcome determined by the probability amplitudes of the various states in the superposition.

Mathematically, if a quantum system is in a superposition $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$, a measurement will yield the outcome $|0\rangle$ with probability $|\alpha|^2$ and the outcome $|1\rangle$ with probability $|\beta|^2$. The act of measurement forces the system into one of these basis states.

Fig 11. The Measurement Card

The Measurement card in QNO! reflects the quantum measurement process in an intriguing game mechanic. When played after a Superposition card, the Measurement card collapses the superposition, revealing the top card from the draw pile. This simulates the quantum measurement concept, where the measurement forces the system into one of its possible states. Also since the measurement card reveals the top card of the draw pile, it also signifies the inherent non-deterministic and probabilistic nature of quantum measurement.

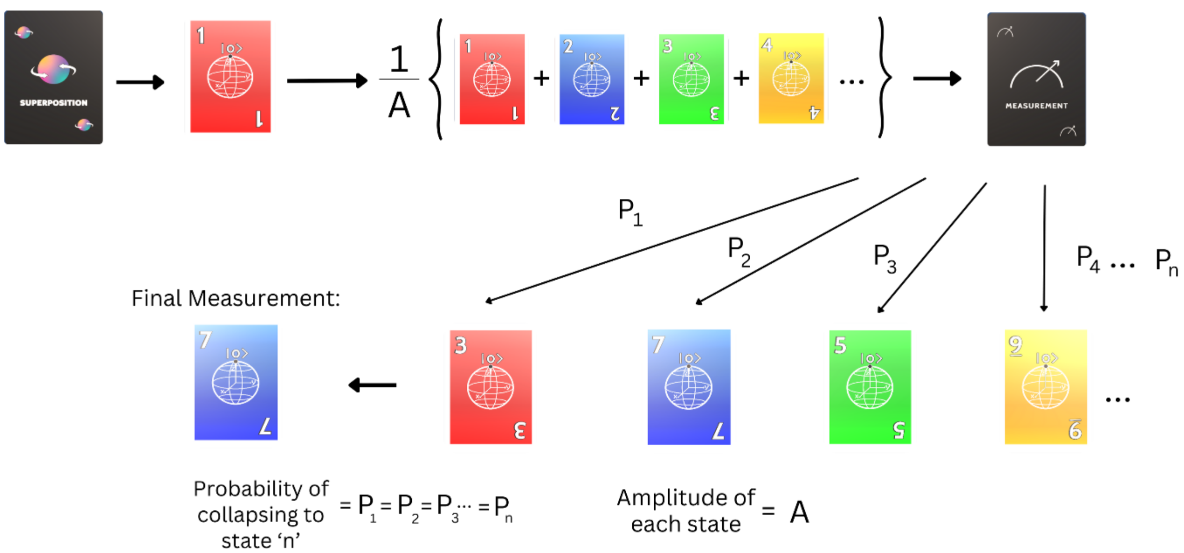

Fig 12. A visual representation of the effect of the Superposition and Measurement cards

Teleportation
Quantum teleportation is a quantum communication process that enables the transfer of quantum information from one location to another with the help of two entangled particles and classical communication. It does not involve the physical movement of particles but rather the transmission of quantum states.

In a simplified explanation, the quantum state of a particle (qubit) is transferred to another distant particle, destroying the original state in the process.

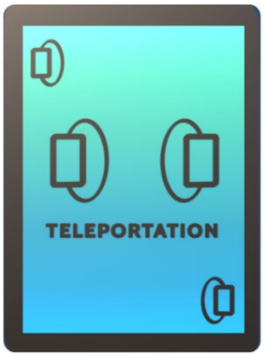

Fig 13. The Teleportation card

The Teleportation card in QNO! captures the essence of quantum teleportation in a playful manner. When a player plays the Teleportation card, they have the ability to choose one card from any other player's hand, effectively "teleporting" it to their own hand. This mirrors the quantum teleportation process where the state of a quantum particle is transferred from one location to another. This intuitively shows that a quantum state is being destroyed at the original location (opposing players hand) and is being teleported to another location (another players hand).

Entanglement
Quantum entanglement is a phenomenon in quantum mechanics where two or more particles become correlated to the extent that the state of one particle instantly influences the state of the other, regardless of the distance between them. This phenomenon violates classical intuitions about separability and suggests an intrinsic connection between entangled particles.

In an entangled state, the measurement of one particle's property instantaneously determines the corresponding property of the other particle. This correlation persists even if the entangled particles are far apart, indicating a non-local connection that defies classical physics.

The Entanglement card in QNO! mirrors the concept of quantum entanglement within the game's dynamics. When a player plays the Entanglement card, they are given the option to choose one card each from two different opponents. Both chosen cards are then placed face down on top of the discard pile, creating an entangled state. This is done to show that in a state of entanglement, similar to superposition, the particle is in a combination of its component basis states.

Fig 14. The Entanglement card

At this stage of the game, normal play stops, and each subsequent player must play the Measurement card to collapse the entangled state. If they lack the Measurement card, they are forced to draw two cards from the draw pile. This process continues for all subsequent players. This process is repeated until a person doesn't play the measurement card up to a maximum of 2 rounds. If the turn comes back to the original player who played the Entanglement card, they must also draw two cards if the entangled state is still intact. This adds a strategic layer to the game, requiring players to use the Entanglement card judiciously.

When a measurement card is played, the entanglement state collapses similar to how measurement of entangled states of 2 or more qubits, collapses them into their basis states. The player who played the measurement card then has a choice to make, of the 2 cards which were placed on top of the draw pile, he/she shall choose to keep one of the 2 cards while discarding the other card onto the discard pile.

5. Results and Future Scope

5.1 Results

The implementation of the quantum computing card game, QNO!, yielded promising results in terms of achieving its educational objectives. The results obtained from playtesting sessions and participant feedback provide valuable insights into the effectiveness of the game as an educational tool for understanding quantum computing concepts. The outcomes can be categorized into several key areas:

- Engagement and Participation:
  Playtesting sessions demonstrated a high level of engagement among participants. The interactive nature of the game encouraged active participation and sustained interest throughout gameplay.
- Concept Retention:
  Participants showcased improved retention of quantum computing concepts introduced through the game. The association of game elements with quantum principles was well-received, contributing to enhanced understanding.
- Strategic Thinking and Decision-Making:
  The game's strategic elements, especially associated with special cards like Teleportation and Entanglement, promoted critical thinking and decision-making skills among players.
- Accessibility and Inclusivity:
  The game successfully catered to a diverse audience, including students, enthusiasts, and individuals with varying levels of familiarity with quantum computing. The accessibility of the game contributed to a broader reach and inclusivity in the learning process.
- Inspiration for Further Learning:
  Participant feedback indicated increased interest in exploring quantum computing beyond the game. The game served as a catalyst, inspiring players to delve deeper into quantum concepts and consider educational pathways in the field.
- Positive Learning Experience:
  Overall, participants reported a positive and enjoyable learning experience. The gamified approach effectively demystified complex quantum principles, aligning with the project's objective of making quantum computing accessible and engaging.

In addition to a physical card game, a prototype of the game was also developed which can be played on a computer. The game was developed using the Unity Game Engine. However, the game still lacks the feature where multiple players can join a single lobby and play against each other. Yet, the game in its current state, can be played between 2 people while sharing the same computer system.

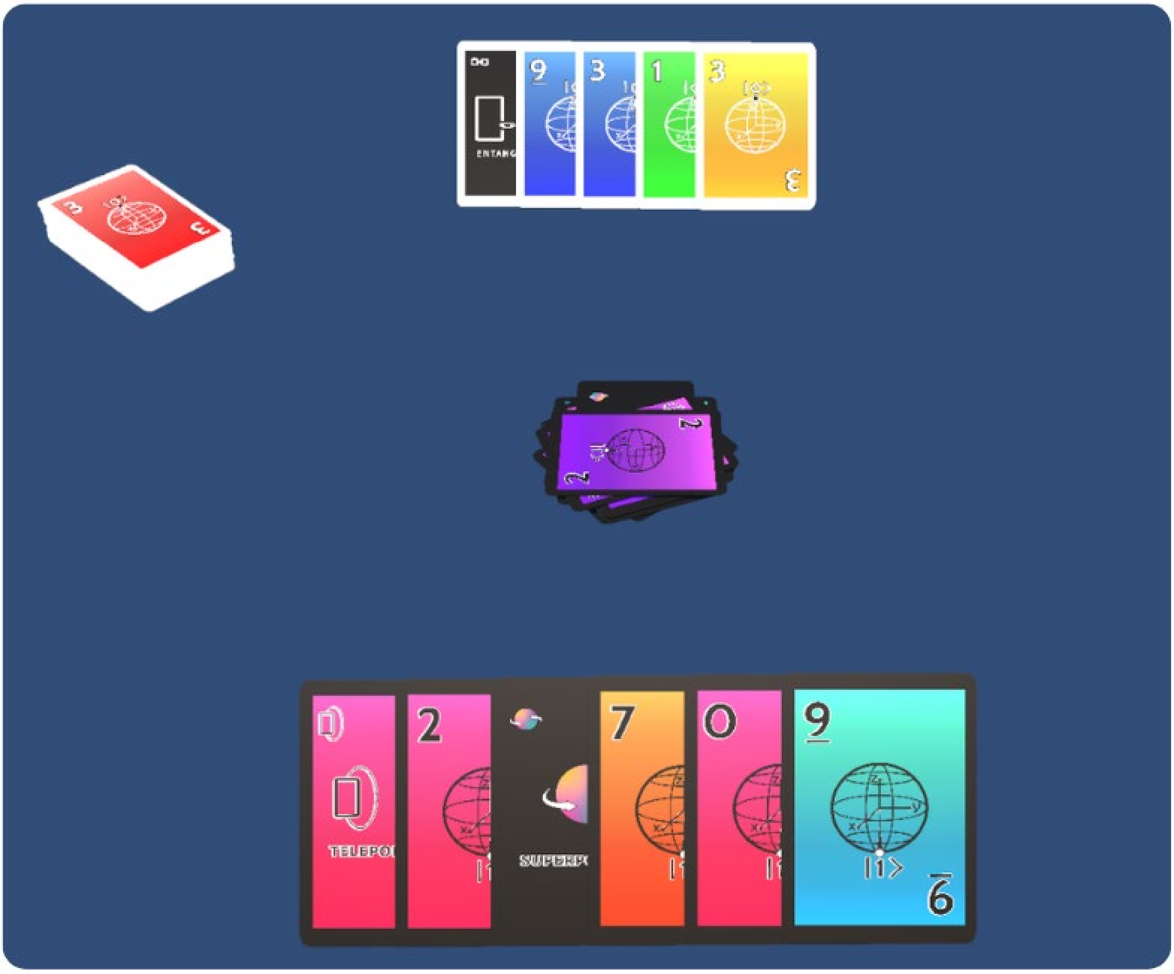

Fig 15. A screenshot from the video game

5.2 Future Scope

The development and initial playtesting of QNO! have laid a solid foundation for future explorations and enhancements. Despite the project's success in engaging participants and conveying quantum concepts, certain limitations, particularly time constraints, hindered the ability to conduct a formal survey to assess the game's efficacy more comprehensively. However, this points toward exciting possibilities for future research and development:

- <u>Formal Evaluation and Survey:</u>
  Conduct a comprehensive survey to quantitatively and qualitatively assess the game's impact on participants' understanding of quantum computing. Include targeted questions to measure knowledge retention, player satisfaction, and the perceived effectiveness of the game in demystifying complex quantum principles.

- <u>Diverse Demographic and Longitudinal Studies:</u>
  Expand participant demographics to include diverse backgrounds and ages, providing a broader perspective on the game's accessibility and educational impact. Implement longitudinal studies to observe the sustained impact of the game on participants' interest in and understanding of quantum computing over an extended period.

- Educational Integration and Continuous Improvement:
  Explore opportunities to integrate the game into formal educational settings, such as classrooms or workshops, to assess its adaptability to structured learning environments. Focus on continuous refinement and iteration of the game based on feedback, emerging advancements in quantum computing, and potential enhancements, ensuring its relevance and effectiveness.

Conclusion

In the dynamic landscape of quantum computing education, the development and deployment of QNO! represent a significant stride toward making this intricate field accessible, engaging, and comprehensible. The amalgamation of game-based learning principles and quantum computing concepts has yielded a promising educational tool. While our initial playtesting and development phase showcased the potential of QNO!, certain limitations, including time constraints preventing a formal survey, underscore the need for ongoing exploration and refinement.

QNO! stands as a testament to the power of gamification in demystifying complex quantum principles. The game's unique blend of entertainment and education has demonstrated its ability to engage players and convey fundamental quantum concepts in an approachable manner. The positive responses from participants during playtesting provide a foundation for future enhancements and widespread adoption.

Looking forward, the future scope of QNO! extends beyond the confines of this initial endeavour. Opportunities for comprehensive evaluations, diverse participant studies, educational integrations, and continuous improvements beckon. As we navigate the uncharted territories of quantum education, QNO! remains a beacon, guiding us toward a future where quantum computing is not only understood but embraced by a diverse and inspired community.

In conclusion, the journey with QNO! has just begun. With the commitment to refinement, expansion, and collaboration, the game holds the promise to be a transformative force in quantum education, fostering a new generation of enthusiasts, learners, and specialists ready to explore the quantum realms ahead.

References

[1] D. Meyer, "Quantum Strategies," Physical Review Letters, vol. 82, no. 5, pp. 1052–1055, Feb. 1999, doi: 10.1103/physrevlett.82.1052..

[2] S. C. Benjamin and P. Hayden, "Multiplayer quantum games," Physical Review A, vol. 64, no. 3, Aug. 2001, doi: 10.1103/physreva.64.030301.

[3] Weisz, Justin & Ashoori, Maryam & Ashktorab, Zahra. (2018). Entanglion: A Board Game for Teaching the Principles of Quantum Computing. 523-534. 10.1145/3242671.3242696.

[4] A. López-Incera and W. Dür, "Entangle me! A game to demonstrate the principles of quantum mechanics," *American Journal of Physics*, vol. 87, no. 2, pp. 95–101, Feb. 2019, doi: 10.1119/1.5086275.

[5] Nielsen, Michael A.; Chuang, Isaac L. (2010). Quantum Computation and Quantum Information (2nd ed.). Cambridge: Cambridge University Press.

[6] Introduction to Quantum Computing - NPTEL-noc iitm https://www.youtube.com/watch?v=2SPjEA-4lKk&list=PLuBwWyD3M82x9PfxeF7oxb0E122mQAWh6