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Master Computer Science

Quantum-Inspired Games:
Gameplay in Quantum Tetris

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Abstract

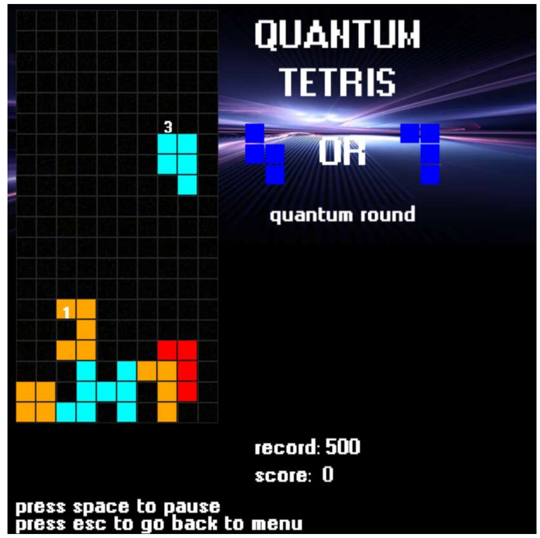
TETRIS is one of the most popular puzzle video games, where players stack tetrominoes in a (typically) 20×10 grid until they are unable to make a move. In this thesis, we propose ways of introducing Quantum Computing principles in classical TETRIS, motivated by the research community's growing interest in studying quantum-inspired games. First, we review related work in the domain of quantum games and existing approaches to QUANTUM TETRIS. Then, we discuss fundamental quantum concepts to set a solid foundation and we integrate them into gameplay by proposing various quantum scenarios and their impact on the game. After that, we describe our QUANTUM TETRIS implementation in detail, along with the rules we included. Moving on to the analysis, we compare the effects and implementation details of QUANTUM TETRIS with other quantum games and we try to define equivalence conditions for classical and quantum game configurations. Furthermore, we propose our research method which includes 20 participants of various academic backgrounds. The results indicate that quantum knowledge does not affect quantum gameplay significantly. Finally, we summarize our findings, name the challenges and limitations in the game design, mention options for further refinement, and propose directions for future research regarding quantum-inspired TETRIS.

Contents

1 Introduction

Before delving into the study of Quantum Games, a brief introduction to the field of Quantum Computing is given. Then, we describe the features and rules of the well-known classical game TETRIS in order to introduce our own quantum-inspired TETRIS implementation later (Figure 1). Finally, we explain the research objective, motivation and limitations behind this work and point out the differences between quantum games and quantum-inspired games.

(a) Game menu



(b) A grid configuration of the quantum version with fixed-age

Figure 1: Screenshots of the QUANTUM TETRIS implementation.

1.1 Quantum Computing

Quantum Computing is the topic that combines Computer Science, Quantum Physics and Information Theory [20]. Quantum Algorithms promise to solve problems significantly faster than the best classical algorithms and, indeed, their computational power has already brought changes in fields like Cryptography, Machine Learning and Chemistry [16].
The most fundamental element of Quantum Computing is the *qubit*, a quantum chunk of information that can be in the state 0, 1, or any linear combination of those states (and therefore in both states at the same time), which is called a quantum *superposition*. Intuitively, this is like operating in two different universes at the same time; one in the state 0 and the other in the state 1. Therefore, an operation on a qubit is equivalent to operating on two different values simultaneously [15]. This property justifies quantum computers' speed and efficiency compared to classical computers.
Apart from the physical implementations in the real world, the theory of Quantum Mechanics is also a great source of inspiration for the gaming industry; many traditional games as well as video games have been enhanced with quantum elements and rules that make the gaming experience more challenging and exciting. Moreover, a quantum game is not necessarily run on a quantum computer, since the logic of a quantum circuit can be simulated by a classical computer. Games are based on probability to a large extent and, thus, generalizing Game Theory to the domain of quantum probabilities is of great interest [10].

1.2 Tetris

Tetris is one of the oldest and most popular computer games. It was created by Alexey Pajitnov in 1985 and it soon became a best-seller around the world [22]. The traditional game uses seven pieces or *tetrominoes*, named according to their similarity to the corresponding letters of the alphabet (see Figure 2), and a (typically) 20-by-10 grid that is initially empty. At the beginning of every round, a tetromino is randomly selected and placed above the middle of the top row of the grid. The tetromino selection is probabilistic. During the game, the piece falls and the player can rotate it and slide it horizontally [2]. The piece stops when it touches another tetromino (in other words, a filled grid square) or the bottom row. Then, the next piece appears and a new round starts. In every round, the player knows the current and the next piece. If all grid squares of a row are filled, the row is cleared; the rows above fall one row lower and the score is increased based on the number of rows cleared.

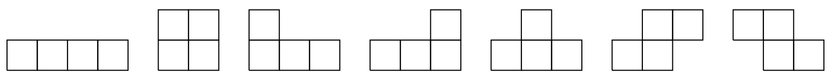


Figure 2: Tetris pieces (I, O, J, L, T, S and Z).

When no more tetrominoes can be placed in the grid (in other words, the filled grid squares do not leave any space for new pieces), the player loses. Since the game continues to generate new pieces until the player loses, the goal of the player is to maximize the score by minimizing the unfilled grid cells in each round and clearing as many lines as possible.

Game gravity in Tetris is a controversial mechanic that can vary in different implementations of the game; pieces either stay in place for the rest of the game or fall lower in the grid every time gaps are created in a row below them. Although it might be more natural, the existence of gravity does not necessarily improve players' experience or gameplay, since they have to focus on dealing with an extra mechanic when making a decision. Alternatively, the lack of gravity can introduce new challenges and potentially more effective strategies. In Section 5 we will justify the choice of lack of gravity for our quantum-inspired version of the game.

Gameplay is seemingly easy in Tetris, but the combinations of possible tetromino positions and rotations lead to a large number of game states. Considering the typical grid size of 20×10 cells, the game states have an upper bound of 7×2^{200} states [18]. Therefore, it would be extremely complex to analyze the state space of the game. Moreover, according to Demaine, Hohenberger and Liben-Nowell [2], it is NP-complete to play Tetris optimally; to maximize the number of single cleared rows or quadruples of cleared rows, to minimize the maximum height of an occupied square, or to maximize the number of tetrominoes placed in the grid before the game is over.

Despite its seemingly simple premise, Tetris has managed to remain relevant and engaging to both scientists and dedicated players of various ages and gaming backgrounds. Even after all these years since its release, the game continues to be a subject of extensive research and analysis because of the attractive combination of simplicity and complexity it incorporates. In the competitive Tetris scene, there is a large community of players that analyze gaming footage and keep developing novel strategies in order to improve their gaming performance as much as possible. Furthermore, some players have even turned their passion for the game into a career by live-streaming their gameplay and competing in tournaments. Tetris is a game

that challenges players' adaptability and problem-solving skills intensely and the possibility of reaching a "dead end" in the game is related to the boundaries of human creativity.
In the following sections, we will refer to TETRIS as classical TETRIS to underline the distinction between this and QUANTUM TETRIS.

1.3 Research Objective

For the purposes of this work, we make a distinction between quantum and quantum-inspired implementations of TETRIS. The QUANTUM TETRIS game developed for this project introduces players to the principles of Quantum Mechanics. However, it draws inspiration from these principles without involving actual quantum systems or operations. It is not required for players to understand Quantum Mechanics in depth to play the game. Instead, quantum aspects are leveraged metaphorically or abstractly to create unique gameplay experiences. In addition, the game does not use any quantum libraries or simulate any quantum circuits. Therefore, it is considered to be closer to the quantum-inspired game category rather than an actual quantum game.
Aside from developing a quantum-inspired version of TETRIS, the main objectives are to analyze the quantum gameplay, compare it with the classical game and share it with players to document their perception of Quantum Mechanics. Specifically, we are interested in knowing how it affects their overall gameplay experience and finding possible relations with potential knowledge in Quantum Computing. Moreover, we aim to discover possible gameplay strategies that can be used in the context of a quantum-inspired game. The quantum version of the game essentially includes different levels (or versions) of "quantumness", depending on how mechanics are implemented. Players are asked to play one game of each version and their scores and feedback are collected at the end. The experimental results are expected to have extensions in the theory of quantum-inspired games; analyzing strategies and optimal moves in quantum-inspired TETRIS could provide novel decision-making and problem-solving insights into Quantum Game Theory. Summarizing, we aim to answer the following research questions:

1. How does background knowledge in Quantum Computing affect players' performance, engagement and overall gameplay experience?

2. Are there differences in players' strategies and decision-making processes between classical and quantum-inspired TETRIS?

The motivation behind this work has many dimensions. Typically, while the development of many quantum games aims to serve science communication (educational or academic) purposes by introducing Quantum Mechanics to people in a fun and interactive way, taking advantage of features of Quantum Physics for further entertainment in a game would also be an interesting aspect. With the constant growth of quantum hardware, multiple new variants of quantum games have emerged in order to utilize the capabilities of quantum computers [25]. Additionally, when it comes to more traditional rather than commercial games, the spread of Quantum Mechanics has managed to inspire developers and researchers to simulate quantum principles in various ways. This work aims to impact the state-of-the-art approaches to quantum-inspired games by proposing different scenarios, using simple game mechanics and user interface. The focus is turned on analyzing players' strategies and interpreting statistical results from the game.

This work is structured as follows. In Section 2 we present some work that inspired this project, as well as the most recent approaches to quantum-inspired games. In Section 3 we give some background knowledge that helps the reader understand the theory applied in quantum games. In Section 4 we analyze some possible concepts to effectively introduce Quantum Mechanics in TETRIS, along with some game rules for each case. In Section 5 we present the QUANTUM TETRIS game implementation created for this project. In Section 6 we study the main differences between our quantum game and other games, as well as the potential configuration equivalence between the classical and arbitrary quantum-inspired TETRIS versions. In Section 7 we discuss the survey procedure and results after testing our game with several participants. Finally, in Section 8, we summarize the key findings and limitations of the research, as well as the challenges of the development procedure, and propose future additions and enhancements regarding the implementation.

2 Related Work

In this section, we mention the most recent studies that inspired the current work. First, although not directly related to QUANTUM TETRIS, we analyze some papers that encourage further experimentation on classical games. Then, we introduce some known quantum-inspired versions of games. Finally, we delve into the existing approaches to quantum-inspired TETRIS, which constitute the main influence for this work.

2.1 Inspiration

One of the most recent studies on TETRIS was conducted for the Fun with Algorithms Conference (FUN 2022) by Dallant and Iacono [6]. This work includes an extensive list of references and exploits the latest results related to the game. The authors consider a slightly different variation of TETRIS and assume that any rectangular piece of any number of squares can be used. The goal is to determine how much time a "greedy" player needs to think before making a move in the game. A player is considered "greedy" when they place a piece focusing on minimizing the vertical space in the current round, regardless of the future pieces. Considering an integer n, the solution to this is keeping track of all the $\mathcal{O}(n)$ possible heights a rectangular piece could fall from. Then, based on the width of a rectangle, the lowest height where it can be placed is found after a binary search through all possible heights.

In their paper, Dorbec and Mhalla [8] focus on introducing Quantum Mechanics in combinatorial games. They propose different rulesets that indicate different ways of playing superpositions of moves in games. They state that the same ruleset can lead to different outcomes in different games.

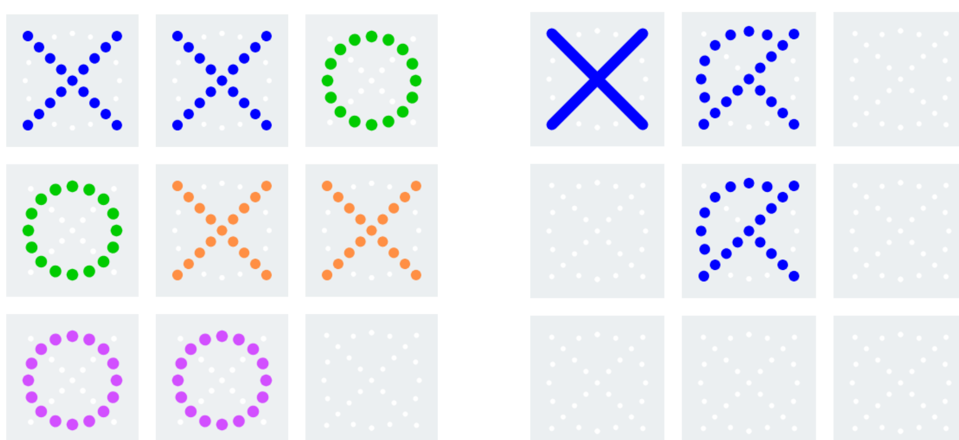
Burke, Ferland and Teng [3] have also studied the structure and complexity of quantum combinatorial games extensively. Specifically, they explore combinatorial games with quantum extensions and analyze their complexity, as well as how quantum moves affect the strategies used in the game. They conclude that the intuitive statement of combinatorial games being at least as computationally hard in their quantum setting as their classical setting is false.

Finally, the work by Phon-Amnuaisuk [18] tries to develop and evolve gameplay strategies in TETRIS using a Genetic Algorithm (GA). The GA was asked to evolve new strategies from 145 different games and the best ones were used to simulate new games. The results showed that the GA could successfully generate new gameplay strategies without having any information about the initial strategies, aside from the unfilled cells in the grid.

2.2 Quantum Games

A quantum game can be described as any type of a playable game that either references or is related to Quantum Physics [19]. In the past decade, many attempts have been made to incorporate Quantum Mechanics in both video games and traditional games. The purpose of this is usually to either introduce people to the world of Quantum Computing and Quantum Physics or ensure that a game is engaging by enhancing its structure or rules. An extensive list of quantum-inspired games can be found at the *Awesome Quantum Games* Github repository. In this section, we will address some of them and discuss a subcategory of Quantum Games, namely Quantum Combinatorial Games.

A very popular game that utilizes quantum phenomena is Quantum Chess by Christopher Cantwell [5]. In Quantum Chess, the pieces can be in a superposition of different squares on the board. When a piece is attacked, a quantum measurement takes place and the superposition collapses based on the probabilities of the piece being placed on the superposed squares. In other words, each action in the game is based on probability and can be completely unexpected. Another game that illustrates the concepts of superposition and entanglement in a simple way is Quantum Tic-Tac-Toe (or Tiq-Taq-Toe) by Evert van Nieuwenburg [23]. Players take turns and place their tokens on a 3×3 grid focusing on placing three consecutive tokens horizontally, vertically or diagonally. The game includes four options; no quantumness, minimal quantumness, moderate quantumness and high quantumness. No quantumness is equivalent to the classical Tic-Tac-Toe game. When the players choose minimal quantumness, they can create superpositions of two tokens by selecting two possible locations in the grid. When the grid is full, superpositions are measured and they collapse independently, leaving only one token from each turn. The game either continues in the same manner, or there is a winner in case three consecutive tokens are formed. In moderate quantumness, a player can entangle their pieces with their opponent's pieces by selecting an empty square and a square that is filled by the opponent's token (see Figure 3). We refer to these moves as "entanglements". When the board is full and the game is measured, the two entangled squares always end up with different tokens. In other words, entanglements provide even more uncertainty in the game by creating dependencies between tokens of different players. Finally, high quantumness is equivalent to the most advanced quantum setting for the game, where players can create entanglements with their opponent's superposition; in other words, three squares are entangled at the same time. This technique assigns probabilities of a token existing in a square which form the final configuration after measurement.



(a) Superposed Tiq-Taq-Toe (b) Entangled Tiq-Taq-Toe

Figure 3: Examples of superposed and entangled states. In (a), squares with tokens of the same color are in a superposition. When the board is full, superpositions collapse. In (b), tokens of different players are entangled and create two Q's. When the board is full, the entangled squares always collapse to opposite tokens.

Combinatorial Games are a large category of games that have caused fundamental interest in developing quantum variants and rules. We define Combinatorial Games as mathematical games with perfect information and without random elements [4]. Since the nature of a game is mostly described by its rules [9], we can define a quantum-inspired framework for a combinatorial game by introducing the ability to make quantum moves as superpositions of classical moves. Quantum moves usually create quantum positions in a game, or *realizations*. A move can only be made if it is legal in at least one realization; legal moves may vary depending on the game. When an illegal move is made, the realization collapses and is eliminated from the possible game configurations in the future. In general, the incorporation of quantum-inspired mechanics in a combinatorial game brings non-determinism into the game space and provides a complex structure that can be used for further additions in the game [3].

2.3 Existing Approaches to Quantum Tetris

One of the early approaches to Quantum Tetris was made by a group of students from Dartmouth University in 2020 to teach the concepts of Quantum Theory using video games [11]. In their implementation, Tetris adopts quantum principles like superposition, entanglement and quantum gates by simulating a quantum computer's "true randomness". A player can use either a regular tetromino or a superposition piece randomly made by two tetrominoes. When a superposition piece hits one of the pieces or the bottom of the grid, it is measured and collapses into one tetromino based on probabilities determined by true randomness. Moreover, some of the superpositions generated by the game are linked and therefore entangled pieces are created. Two identical superpositions appear on the screen and, when they touch another piece or the bottom, they collapse. Since the two superposition pieces are entangled, the final piece of the first superposition depends on the final piece of the second. For example, if a superposition is made of the pieces J and S and the first superposition piece collapses into J, then the second superposition piece will collapse into S. Finally, this variation makes use of two quantum gates to expand the variety of probabilities for the superposition pieces, but the current work will not elaborate on this mechanic.

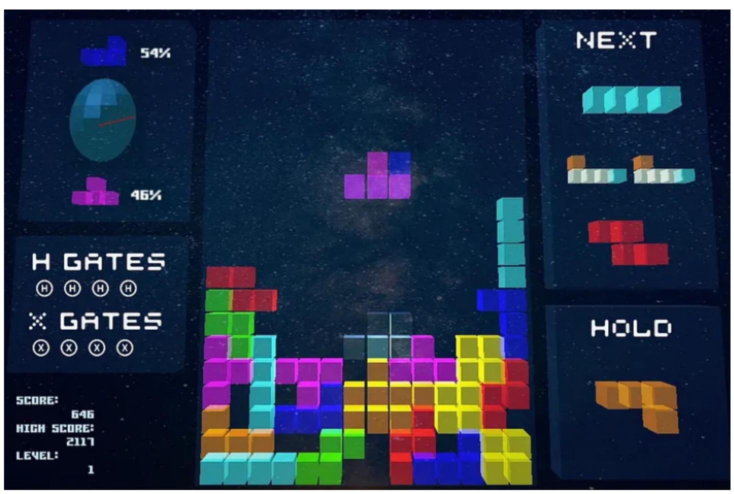


Figure 4: Quantum Tetris approach by Glasgow et al. [11].

Another approach of Quantum Tetris is the winning entry of the Quantum Design Jam from IBM and Parsons from October 2021 [26]. The approach of this implementation is completely different from the previous one. The similarity is that the authors also focus on the concept of true randomness, nevertheless, they exploit the noise encountered in quantum computers. Their game is essentially a metaphor for a quantum circuit. Aside from the classical seven pieces, the quantum computer they use generates "noisy" pieces as a result of miscalculations during the piece generation process. The pieces are unique and unpredictable and do not necessarily obey the "four blocks attached" rule. Although this approach does not display any Quantum Mechanics in the game, but rather uses the power of quantum computers to generate unpredictable pieces, it constitutes the state-of-the-art when it comes to exploiting the capabilities of Quantum Computing for TETRIS.

Figure 5: Quantum Tetris approach for the Quantum Design Jam [26].

3 Background

In the past, researchers in various fields such as Cryptography and Artificial Intelligence have explored how the power of Quantum Computing applies in improving classical frameworks [3]. More recently, the interest has turned to traditional games, where the question that must be answered is when and how quantum decisions can be made in order to improve players' decision-making or experience during gameplay.
Quantum Computing has already started inspiring researchers and game developers to enhance traditional games. Note that, in this work, we care about utilizing elements of Quantum Computing as inspiration to enrich traditional games, rather than studying the implications in Physics.
To understand how quantum rules can be applied to a game, it is important to analyze the basic concepts of Quantum Mechanics. The main phenomena of Quantum Computing are superpositions and entanglements.

3.1 Quantum Bits

Similarly to bits, which are the fundamental concept of classical computing, quantum bits (or *qubits*) are the fundamental concept of Quantum Computing. Qubits are abstract mathematical objects that, unlike bits, allow us to create the theory of quantum computation without relying on a specific system [17]. Each qubit has a state, which can be 0 or 1 just like bits, but it can also be any other linear combination of 0 and 1. States in Quantum Mechanics use the Dirac notation; a qubit can be in the state $|0\rangle$, $|1\rangle$ or $\alpha|0\rangle + \beta|1\rangle$ for some complex numbers α, β. Therefore, a quantum state is a linear combination of classical states. Generally, a qubit state can be seen as a vector in a two-dimensional vector space where $|0\rangle$ and $|1\rangle$ form an orthonormal basis in this vector space.
Before measuring a qubit, the information we get is much more restricted compared to a classical bit. It is impossible to know the exact state of a qubit or, in other words, the numbers α and β. In general, considering state normalization ($|\alpha|^2 + |\beta|^2 = 1$), the measuring results can be either $|0\rangle$ with probability $|\alpha|^2$ or $|1\rangle$ with probability $|\beta|^2$. This effect of unpredictability in a quantum system is the biggest difference between classical and Quantum Computing. One cannot directly correlate elements of a quantum system to elements of the real world. However, this abstract behavior can be manipulated and give an outcome dependent on the properties of a state [17]. This procedure in Quantum Computing is called measurement.

3.2 Superposition

As mentioned before, the state of a qubit is a linear combination of classical states, written as a vector of amplitudes. This linear combination is called a *superposition*. When a qubit is in superposition, it exists in a continuum of states between $|0\rangle$ and $|1\rangle$ and therefore we cannot "see" it until it is measured and gives the output "0" or "1" probabilistically [7]. The outcome that we observe is classical.
We argued that a superposition of states can be written as

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

where α and β are complex numbers. The exact values of α and β are not known in advance and therefore the final state cannot be determined before measurement. The numbers $|\alpha|^2$

and $|\beta|^2$ are the probabilities of being in the state $|0\rangle$ or $|1\rangle$ and, therefore, $|\alpha|^2 + |\beta|^2 = 1$ holds.
Intuitively, the concept of superposition in games refers to simultaneous states or configurations that overlap within the same environment [12]. Regarding puzzle games like TETRIS, objects can exist in multiple states until an action or condition collapses them into a final state. This action or condition is equivalent to the observation and measurement in Quantum Mechanics.

3.3 Entanglement

Another non-intuitive phenomenon of Quantum Mechanics is entanglement. Two (or more) qubits are entangled when one's quantum state is dependent on the other's regardless of the distance between them. This connection between states is revealed after measurement, since the measurement outcome on one qubit is always correlated to the measurement on the other qubit.
Consider the following example:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

By observing one of the two qubits of $|\psi\rangle$, the other will collapse to the same value (they have the same amplitudes which sum up to one). These qubits are therefore correlated [13].
If we try to define entanglement as a quantum concept in puzzle games, it expresses the interconnection between game elements. When two elements are entangled, the state of the one affects the state or the outcome of the other. As a result, the player can have information about the second element if the entangled element is revealed.

4 Quantum Mechanics in Tetris

We introduce two ways of adapting Quantum Mechanics, namely superpositions and entanglements, in Tetris. The first is creating random superpositions of two pieces that fit in a 2×3 bounding box. We analyze how using bounding boxes works and affects gameplay. Second, we define the concept of piece aging; an (integer) "age" is assigned to every superposition, which indicates the moment of its collapse into one of the two pieces. We discuss different age scenarios, the moment that a row clearance occurs and the way the score is affected in each case.

4.1 Tetromino Superposition

Quantum superpositions are the main concept of Quantum Tetris, since not only are they the most natural way to add "quantumness" to the classical game, but they also constitute the basis for the creation of entanglements, as we will discuss later. To experiment with the available space and time in the game, the bounding box and aging concepts are introduced accordingly.

4.1.1 Bounding Box

As mentioned before, the game creates superpositions of two pieces that fit in a 2×3 bounding box. Those pieces are S, Z, L, J and T. As a result, the only thing visible to the player is a combination of the two randomly selected pieces. Note that these superpositions are not "boxes" in the strict sense, since some of them have "holes". Instead of creating a perfect 2×3 rectangle for any piece combination, we create an abstract rectangular shape by letting the two selected pieces overlap. It is then easier for the player to understand which pieces the superposition consists of. All possible superpositions of combining different bounding box pieces can be seen in Figure 6. Note that the superposition pieces are generated with an initial orientation like in Figure 2. Finally, when the bounding box mechanic is used in the game, we assume that pieces I and O always behave classically. Note that we allow superpositions of the same piece (for instance, two L's), which also implies classical behavior.

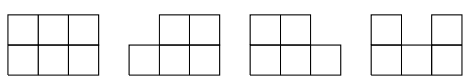


Figure 6: Bounding box superpositions — The first superposition can consist of S and Z, or J and S, or L and Z. The second superposition can consist of S and L, or T and L, or S and T. The third superposition can consist of Z and J, or Z and T, or J and T. The fourth superposition consists of L and J.

In the implementation, there is a distinction between classical and quantum rounds. A quantum round consists of a superposition and the player knows the two possible pieces in advance. A classical round consists of an I, an O, or any of the bounding box pieces in case the same piece is chosen twice for a superposition. When a bounding box superposition is played, the only thing known to the player are the possible boundaries that the two pieces create.
Summarizing, the bounding box mechanic is a way of incorporating quantum superpositions in classical Tetris. It adds a layer of complexity to the game, which means players must adapt their strategy depending on whether the round is classical or quantum.

4.1.2 Aging

After determining how superpositions are generated in the game, it is important to decide the moment a superposition collapses into a final classical piece. We choose the moment a superposition collapses by assigning an age to it, which we assume is known to the player. The motivation for developing the aging concept stems from the fact that quantum states slowly "decohere", which means that they become more classical after several actions occur.
We consider the following scenarios:

Scenario 1. *(minimal-age) Superpositions collapse at the end of the round, after being placed in the grid. This implies that rows are cleared immediately, both for classical and quantum pieces.*

Scenario 2. *(fixed-age) An age n is assigned to every generated superposition. At the end of every round, each age is reduced by 1 and a superposition whose age becomes zero collapses. It is not allowed for superpositions to clear rows before they collapse.*

Scenario 3. *(maximal-age) When the grid is full and the last piece is placed on the stack, all superpositions collapse and only classical pieces remain in the grid. Superpositions cannot clear rows before their collapse. After everything is collapsed into a final piece, the grid is reorganized by moving pieces lower based on game gravity. In the end, rows are cleared normally.*

The main rule behind all scenarios is that the order of collapse and row clearance matters. The game is initially considered to be in a quantum state, even when a classical piece is generated instead of a superposition because row clearance is not allowed before a piece collapses into its final state. In Scenario 1, a piece collapses the moment it touches a piece in the grid or the bottom (see Figure 7). Therefore, a row can be cleared immediately. In Scenario 2, depending on the initial age of the pieces, one superposition collapses in every round (see Figure 8) Note that, in Figure 8, we omit the pieces generated after the red superposition to keep the focus on its collapse. A row can be cleared only when it consists of classical or collapsed pieces. In Scenario 3, when the grid is filled, every quantum move collapses and the grid is reorganized (see Figure 9). The game is no longer in a quantum state and rows are cleared as usual; we can assume that row clearance starts from the bottom because this rule aligns with game gravity. In general, there are multiple TETRIS variants with different row-clearing and gravity rules depending on the scope of each implementation. Some games apply the cascade mode gravity, where the system is recursive and reapplies gravity after each row clearance to check for possible subsequent line clearances [1]. Another option is the "naive" gravity, which essentially leaves floating unconnected blocks after a row clearance. In Section 5 we explain why we chose to use "naive" gravity for our QUANTUM TETRIS implementation.
Since the main goal in TETRIS is to keep increasing the score by clearing rows, it is reasonable to investigate how the score is affected in every quantum scenario we defined for the game. Scenario 1 is the closest to the classical version of the game. At the end of every round, every piece in the grid is classical. When the grid is full, the game is over and the score is reset to zero. In Scenario 2, rows can only be cleared by classical or collapsed pieces. Similarly to the first scenario, the game is over when no more pieces can be placed and the remaining superpositions cannot collapse, because their age is greater than zero. In Scenario 3, there can be different ways of handling the current score. Superpositions cannot clear rows before their collapse and therefore the score can be increased only when classical pieces clear a row.

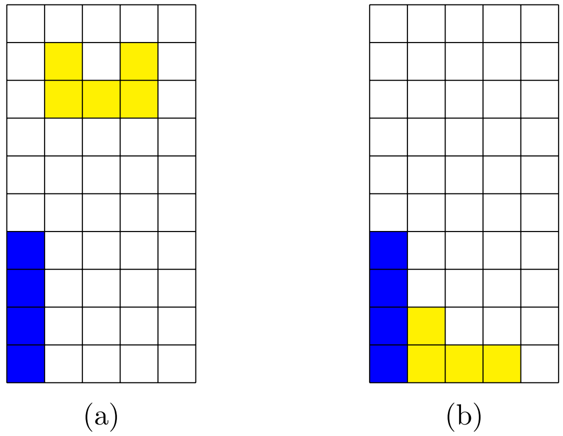


Figure 7: **Scenario 1** — A superposition is generated and it collapses the moment it is placed in the grid.

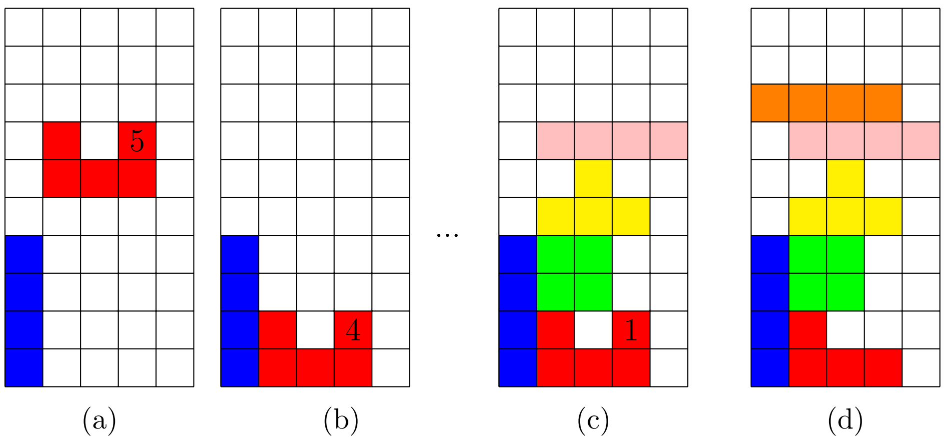


Figure 8: **Scenario 2** — A superposition of age equal to 5 is generated. The age is decreased by 1 in every round and, when it goes to zero, it collapses.

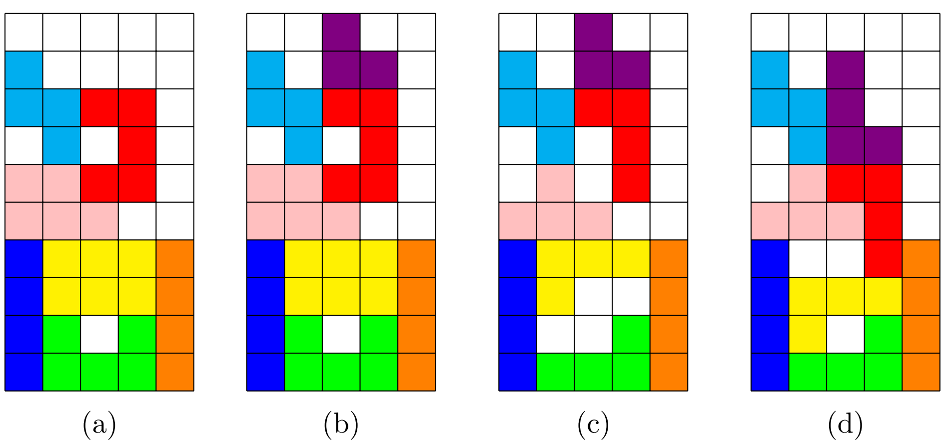


Figure 9: **Scenario 3** — Superpositions are placed in the grid without clearing rows. When no more pieces can be placed, superpositions collapse at once. The grid is reorganized and then, if possible, rows are cleared.

When the grid is full, all superpositions collapse at once, pieces fall to their final locations and,

if necessary, rows are cleared. The game starts over from the current classical configuration, instead of an empty grid.
Regarding the score, it remains the same and it can be increased in the new round, but the moment of resetting it to zero can vary in different cases. If we assume that quantum rounds are repeated until a collapse occurs but at least one piece remains at the top row of the grid and therefore the game is over, then this is a case where the player could achieve the maximum score. Another case could be that the collapse at the end of the round happens only once. After that, every round is either classical or quantum with immediate collapse. Any combination of these cases implies that, in the next grid filling, the game is over and the score is reset. In is worth mentioning that, when we say that a superposition collapses at the end of the round, we mean that it is either placed on an existing piece in the grid or it has reached the bottom of the grid.
As mentioned above, the order of collapse and row clearance can affect the gameplay. Another issue that needs to be addressed is how the collapse happens; namely, which pieces collapse first. If we do not consider any specific rules for age assignment, an intuitive case is where pieces start collapsing from the bottom of the grid and then everything falls into their final positions. This case would be equivalent to the case where all pieces collapse simultaneously, since the collapsed pieces would fall to their final locations exactly after their collapse and therefore the final configuration at the end of the round is the same in both cases.
Note that, in Scenario 3, we assume that one action happens at a time; first, the superpositions collapse. Then, the pieces that have now become classical are dropped into their final locations in order. Finally, rows are cleared where possible; in the case of Figure 9, the first and third rows will be cleared immediately after configuration (d). Overall, the order of collapse does not affect the way the game continues.

4.2 Tetromino Entanglement

To incorporate quantum entanglement in TETRIS, we need to ensure that two pieces that create a superposition are entangled; the final state of one piece depends on the final state of the other. We will define and analyze two possible scenarios of incorporating entanglement in TETRIS.

Scenario 4. *Entangled pieces are used in the same round. The game generates a bounding box superposition that appears in the grid twice, in mirroring positions. The superpositions can be rotated in a mirroring manner and they collapse at the end of the round. When this happens, the two entangled pieces appear in the position where the player has put the corresponding superpositions.*

Scenario 5. *Entangled pieces are used in different (consecutive) rounds. The game generates a bounding box superposition that appears once, like in the superposed version of the game. At the end of the round, it collapses into one piece, which is still interconnected with the second piece of the superposition. This piece is played in the next round classically. In other words, quantum rounds and classical rounds alternate.*

The two scenarios differ in the way that the tetromino entanglement is presented in the game. In Scenario 4, there are two identical superpositions that consist of two entangled tetrominoes (see Figure 10). The player has to place both superpositions in the same grid, at the same time. They collapse simultaneously at the end of the round and the final outcome

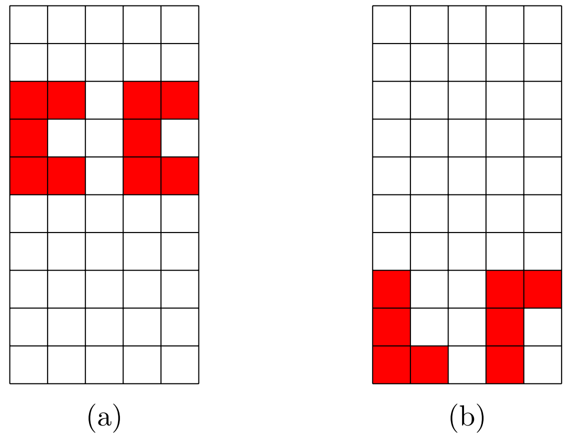


Figure 10: **Scenario 4** — Entangled pieces are played in the same round.

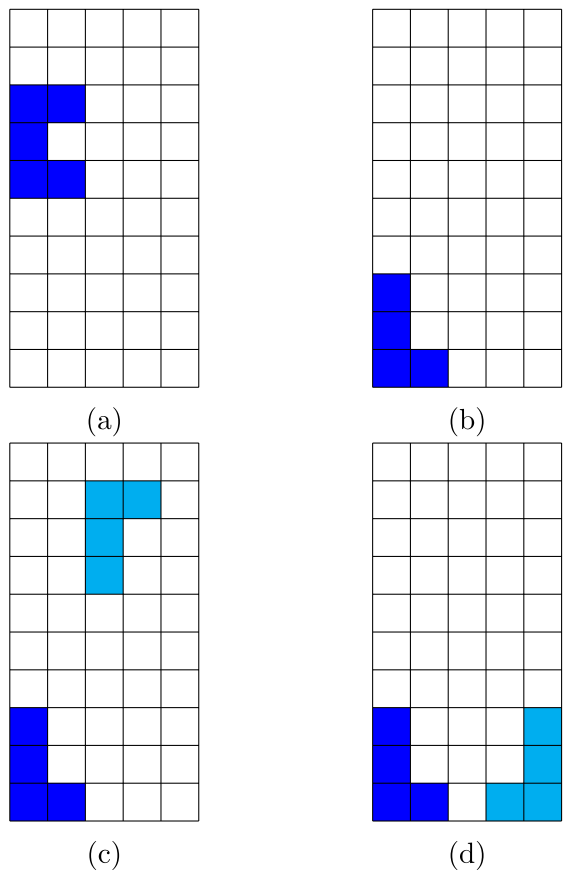


Figure 11: **Scenario 5** — A superposition collapses ((a), (b)) and the entangled piece is played in the next round classically ((c), (d)).

of the one superposition depends on the other. The main difficulty in this scenario is that, considering the classical grid size, the player only has half of the horizontal space to move a superposition. On the other hand, Scenario 5 combines rounds of superpositions of minimal-age, namely Scenario 1, and classical rounds (see Figure 11). A single superposition of two entangled pieces is generated and it collapses into one of the pieces at the end of the round. The pieces remain entangled after the collapse and the second piece is played in the next round classically. This means that a classical round follows every quantum round.

The conclusion coming from the two entanglement scenarios is that entangled pieces are still hidden behind superpositions. Note that it is always the case that a bounding box consisting of two entangled pieces is generated, therefore classical pieces (I and O) are not used in this quantum version. In general, classical rounds could exist in entangled TETRIS, but in this work we assume that a superposition is always implemented as a 2×3 bounding box of pieces of the corresponding size. Finally, in both entanglement scenarios, the collapse and row clearance occur in the same manner as in the superposition scenarios, since entanglement scenarios are essentially extensions of Scenario 1.

5 Implementation

Following the analysis in Section 4, we will now focus on the different quantum variations we implemented. This section is dedicated to the setting of our own QUANTUM TETRIS implementation (see Figure 13). The game was created in Python using *pygame* and is based on a simple classical TETRIS implementation [21].
Starting with the basic elements of the classical game, a 10×20 grid and the seven tetrominoes are created. Tetrominoes are placed in a coordinate system like in Figure 12, so that each piece has a fixed center of rotation. The coordinates corresponding to each tetromino are the coordinates of the center of rotation of each cell that belongs to the tetromino. The frame rate for the tetrominoes is set to 60fps and a color is assigned randomly from the list of the official colors in TETRIS {red, green, blue, cyan, magenta, yellow, orange}. The scoring system is defined based on the TETRIS NES Video Game [24], but the score does not escalate in each round to maintain non-complexity. A single row clearance offers 100 points, a double offers 300 points, a triple offers 500 points and a quadruple (or "tetris") offers 800 points. In addition, a border-checking function is used to ensure that pieces do not exceed the x and y limits of the grid.

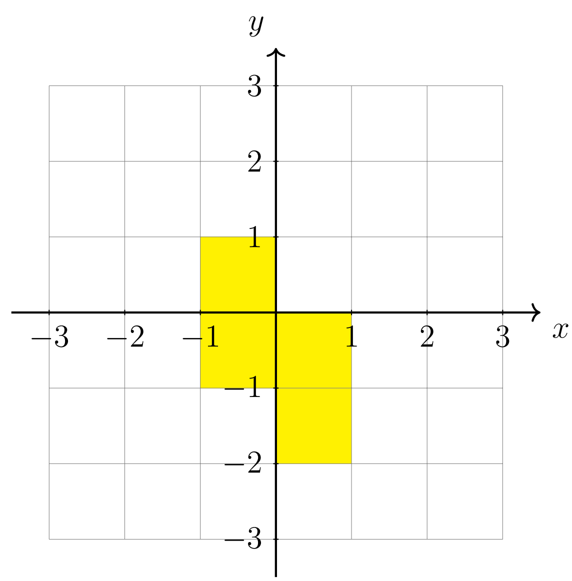


Figure 12: Example of an S figure placed in a coordinate system.

The game starts when a tetromino is randomly selected and placed in the middle of the grid. In order to display the tetromino of the next round, the next tetromino is also randomly selected. The main idea behind the final tetromino position is that it should continue falling until the condition of either reaching the bottom or touching an existing piece is met. When this happens, a copy of the piece remains in the grid and the current piece is now the next piece which was earlier selected. As expected, the pieces can be rotated by the player. The O piece has only one orientation, I, S and Z have two, and L, J and T have four. The rotation of a piece happens by rotating each cell in the piece around its center of rotation. Regarding row clearance, we iterate through filled tiles of all 20 rows. We use a counter so that we move to the next row only when the line is incomplete. The filled lines are then overwritten from above. After one or more lines are cleared, the score is updated. Finally, the game is over when no more pieces can be placed in the grid. When any tetromino reaches the upper limit of the plain field, the record-setting function is called and the game map is cleared. The parameters for the animation speed and the score are reset and the game restarts.

The current classical implementation of TETRIS uses "naive" gravity, which means that a row clearance may lead to unconnected cells floating in the grid. For this reason, we decided not to try Scenario 3 of maximal quantumness in this setting. This scenario is essentially based on the grid configurations being rearranged after the simultaneous piece collapse, thus it would be difficult for players to continue the game when pieces are floating in random positions in the grid.

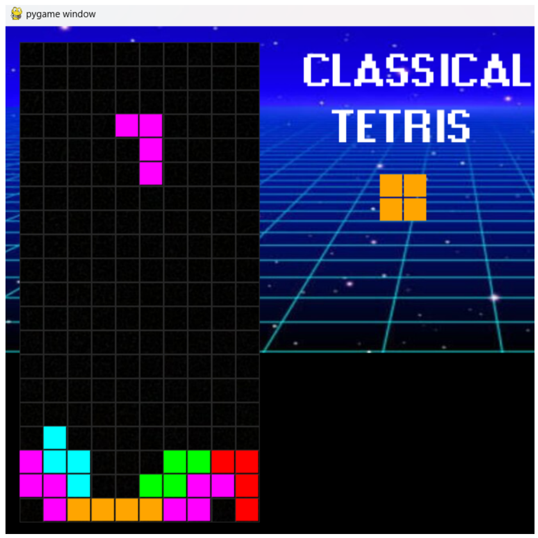
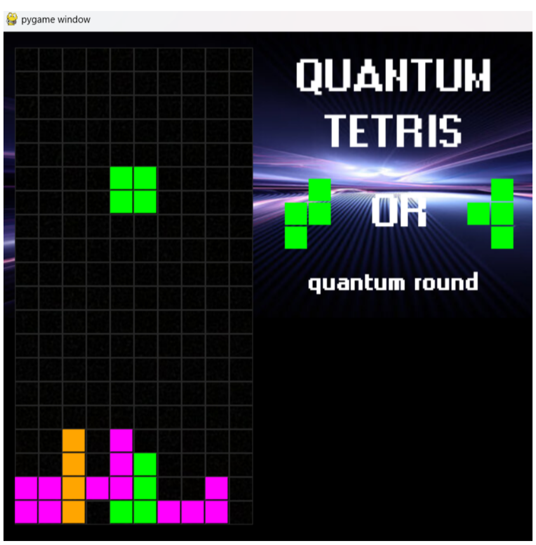
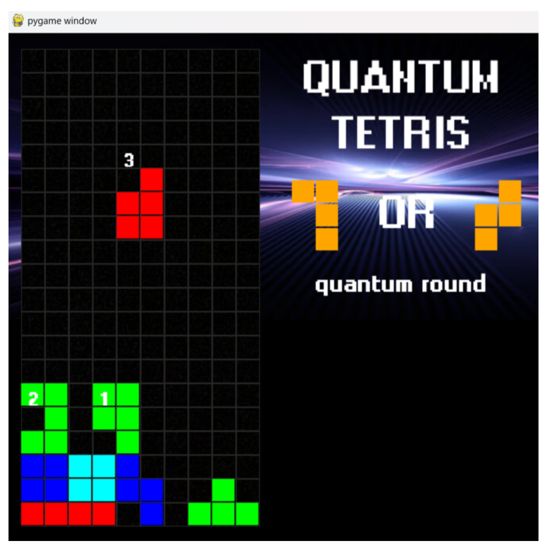


Figure 13: Screenshot of the classical TETRIS implementation.



(a) minimal-age QUANTUM TETRIS



(b) fixed-age QUANTUM TETRIS

Figure 14: Screenshots of the superposed QUANTUM TETRIS implementation; minimal-age (a) and fixed-age that equals to three (b).

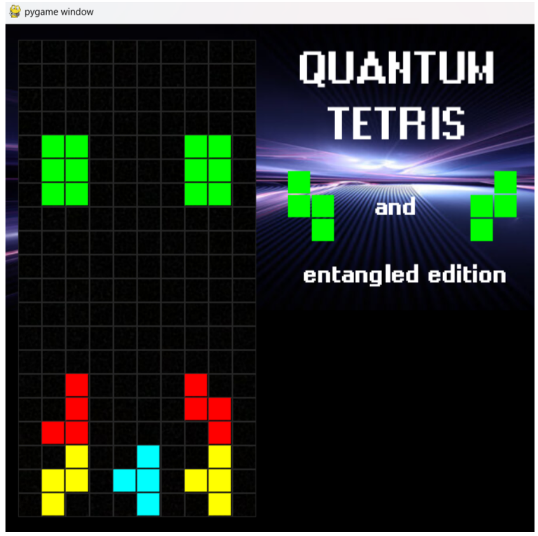


Figure 15: Screenshot of the entangled QUANTUM TETRIS implementation.

5.1 Superposed TETRIS

We will now explain the quantum-inspired additions to the classical game, starting from tetromino superposition. We decided to implement Scenario 1 and Scenario 2 for the superposed version. First, we create a function in order to implement bounding box superpositions. We start by selecting a random tetromino out of the seven tetrominoes. The function takes this tetromino as an argument and determines the shape of the second tetromino needed for the superposition. We want I and O to behave classically in the game, therefore we check whether the selected tetromino is an I or an O and if this is the case then the second tetromino is a copy of the first one. In this case, the two tetrominoes behave as one and the round is classical. We will refer to I and O tetrominoes as classical tetrominoes for convenience. If the selected tetromino is an S, Z, L, J or T it means that it fits in the required bounding box and a superposition can be created. For this, we need the second tetromino to be randomly selected from the same list of five pieces.

5.1.1 Minimal-Age

We consider the minimal-age (or "minimal quantumness", see Figure 14a) version to be the case where a superposition collapses immediately at the end of the round, namely when it either reaches the bottom of the grid or another existing piece. To implement this mechanic, we randomly choose between the two pieces that form the superposition that is currently falling and, when the border-checking condition is violated, the superposition collapses into the chosen piece. The characterization "minimal" stems from the fact that the quantum effect is only present until the end of each round.

In this implementation, we assume that the collapse of a superposition can lead to two different outcomes with equal probability. Rows can be cleared only the moment after a superposition collapses, in case of a quantum round. When the collapse occurs, the remaining piece either stays in place or slides down to fill possible gaps.

The example in Figure 16 displays the two possible game outcomes after placing a superposition consisting of a Z and an S. If the superposition collapses into a Z, then the row is not cleared. On the other hand, if it collapses into an S, then the piece can slide into the gap in the grid

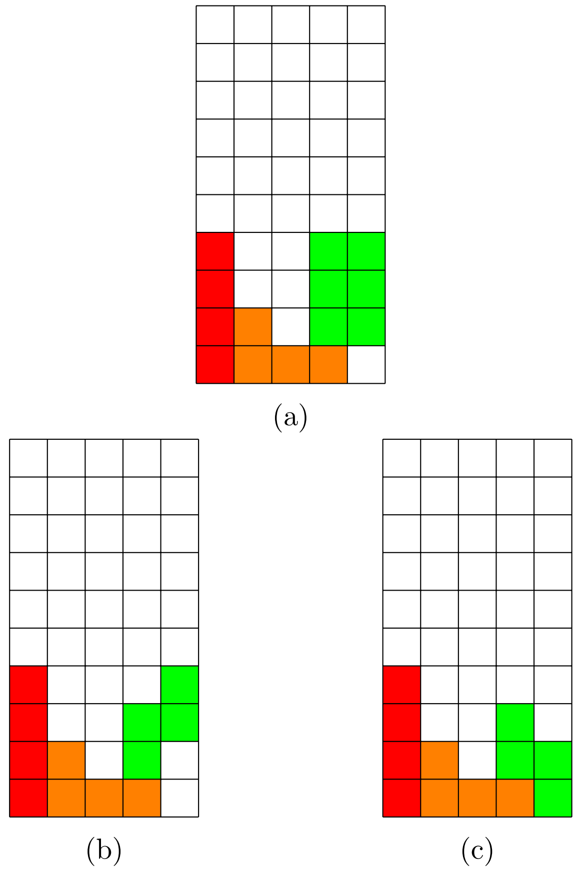


Figure 16: A superposition of a Z and an S piece is ready to collapse (a). The collapse can lead to two different configurations equiprobably, with the final shape being either a Z (b) or an S (c).

and clear a row, which implies that the player's score is increased. This is an example of how the smallest quantum-inspired effect in the game can create uncertainty and unpredictability in a seemingly easy game.

5.1.2 Fixed-Age

In this version, a constant age n is assigned to each superposition. The player can choose the superposition age, but we set the age to be equal to three as default (Figure 14b). Each superposition is generated with the same age, which is reduced by one at the end of every round, and the collapse occurs when the age becomes zero. The game keeps track of every superposition placed in the grid, along with its age.
Similarly to the minimal-age scenario, the moment of a collapse is known by the player. The difference is that, in this case, the game does not keep any information about the superpositions after they collapse, which means that collapsed pieces stay in place and the usual game gravity is not applied. Since gap filling and row clearance are not guaranteed after a collapse, the gameplay can create "holes" in the grid. The reason we decided to use an implementation without (or with "naive") game gravity is to challenge players and test their adaptability, especially when combined with quantum-inspired mechanics. "Naive" gravity is considered to set limits to player strategies concerning field management, which is a favorable option compared to cascade gravity because it can result in more controlled line clearance. Players

are expected to focus solely on piece placement and it is crucial to consider that, after a superposition is collapsed, the final position of the piece is determined with no possibility of change in future rounds. The lack of gravity can also encourage creative gameplay with unconventional stacking and innovative solutions to clearing lines.
Figure 17d depicts the final configuration of a superposition that starts with an age of two, collapses after two rounds and clears a row. It is clear that game gravity does not apply, therefore the player must focus on filling rows that are already occupied by cells. Note that floating cells in the grid can only result from a collapse; as said earlier, row clearance can only occur with classical or collapsed pieces. Therefore, if a classical piece is stacked on top of a row that is about to get cleared, the piece moves lower like in the classical case. When a collapse interferes with a row clearance, "naive" gravity is applied and floating cells remain in the grid (see yellow cells in Figure 17d).
Regarding the order of row clearance, it is worth mentioning that the "naive" gravity rule makes rows independent from each other, meaning that a row is always cleared if it consists of cells that belong to a classical piece (either I, O or a collapsed piece). This means that a row can be cleared regardless of having a quantum piece overlapping with a row above or below (see Figure 18).

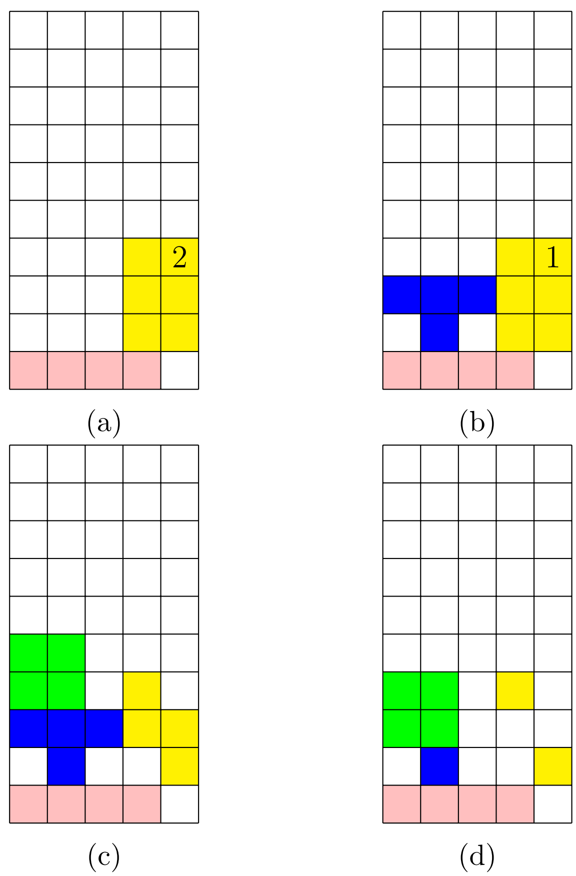


Figure 17: A superposition with a fixed-age of two collapses and a row is cleared. Gravity does not work for unconnected blocks of collapsed pieces.

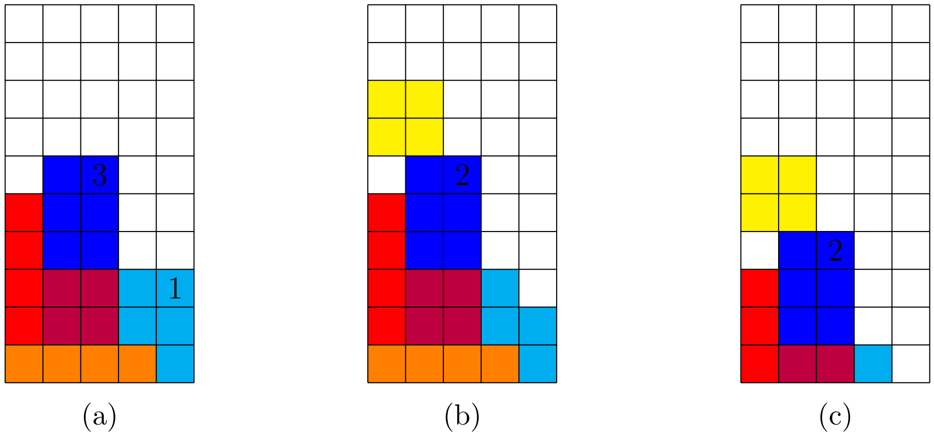


Figure 18: Example of row clearance with "naive" game gravity. Superpositions in other rows do not affect the current row. Note that (b) and (c) refer to the same round; (c) visualizes the final configuration after the bottom row clearance.

5.2 Entangled TETRIS

Continuing with the quantum-inspired mechanics, we will focus on implementing Scenario 4 for the entangled version of QUANTUM TETRIS. In this scenario, the game generates classical pieces or bounding box superpositions, exactly like the superposed versions of the game. However, the pieces in a superposition are now entangled; the states, or in TETRIS terms, the shapes of the pieces are correlated to each other. The interpretation of the entanglement phenomenon in QUANTUM TETRIS is that the superpositions generated from the game consist of in principle entangled pieces that should both be used in the same round (see Figure 15). A superposition appears twice in mirroring positions in the grid. The player can move and rotate them as usual, but only half of the horizontal space is available for each superposition. In the case of a classical piece, it is played as normal.

This entangled version of TETRIS is expected to be the most challenging one, because of the different setting of two superpositions per round. Similar to the superposed version, the tetromino placement creates "holes" that the player has to deal with.

6 Analysis

We discuss how quantum-inspired mechanics are implemented and interpreted in our own Quantum Tetris implementation and other existing quantum games. Furthermore, we aim to discover what kind of rules and conditions must hold so that classical Tetris configurations are constructible in an arbitrary Quantum Tetris instance, if possible.

6.1 Comparing Quantum Games

Since Quantum Tetris gathers inspiration from various versions of already existing quantum games, some of which we discussed in Section 2, it is worth mentioning some similarities and, mostly, differences in the implementations of the above.
Starting with the Quantum Tetris version by Xiao, Lari, Ho, Parekh and Brückner [26] for the Quantum Design Jam, the creators focused on utilizing the main feature of quantum computers, namely "true randomness", in order to create abstract, unpredictable and unique tetrominoes. They translated the game into a quantum circuit which produces more noise as the game continues and, as a result, more irregular tetrominoes are generated. In contrast, the Quantum Tetris version by Glasgow, Levy, Hilton and Brantley [11] is similar to the current version; the creators also use the most significant principles of Quantum Mechanics to make a more engaging and creative game. The superposition and entanglement mechanics in their version are equivalent to the implementation of Scenario 1 and Scenario 4 in Section 4.2. However, the design of their implementation allows players to distinguish the two tetrominoes that form a superposition instead of only revealing a rectangular bounding box as defined in Section 4.1.1.
Finally, if we compare Quantum Tetris with a different quantum game like Tiq-Taq-Toe [23], we will observe that the same quantum-inspired mechanics are implemented in very different ways in the two games. A major difference is that in Quantum Tic-Tac-Toe a superposition is created by the players, whereas the game generates superpositions in Quantum Tetris. As already discussed in Section 2.2, in Tiq-Taq-Toe the players can form superpositions using any pair of squares in the grid. The superpositions collapse only when the grid is full of tokens and the collapse occurs simultaneously for all superpositions, which do not affect each other in the game. On the other hand, Quantum Tetris uses the bounding box technique for better user-computer interaction, where I and O pieces behave classically. Various options can be determined for the moment of collapse and there are cases where superpositions might affect each other, depending on their location in the grid.

6.2 Equivalence between Classical and Quantum-inspired Tetris

In Section 4, we defined a small number of scenarios that could theoretically embody quantum features in Tetris. However, the possibilities of combining Quantum Mechanics with the classical game are endless and depend on the developer's goals. A question that arises is which configurations of Tetris are constructible in a theoretical version of Quantum Tetris. We assume that a Tetris configuration is defined as a game board with some already occupied cells, and a configuration is constructible if it can be reached from an initially empty board after a sequence of pieces with appropriate rotations [14]. In the classical game, a tetromino placement in the grid leads to a fixed outcome and, therefore, all configurations are deterministic. In Quantum Tetris, tetrominoes exist in superpositions which means that

multiple cells are occupied simultaneously and their final state (either existing in the grid or not) is not predetermined until collapse.
If we consider any scenario that obeys the bounding box rule, where superpositions of the same piece are allowed, then every classical configuration is theoretically possible, assuming that a superposition of the same piece in the quantum game corresponds to a classical piece in the classical game. It would be interesting to consider a case where only superpositions of different pieces are allowed and the only classical possibilities are I and O, like in the implementation. In this case, it is not possible to use any kind of classical pieces except I and O, therefore every configuration will include (not necessarily collapsed) superpositions that must somehow generate a classical instance.

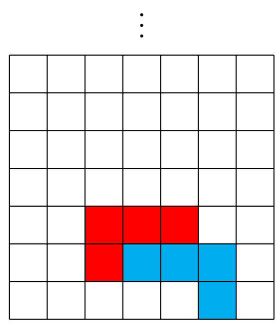


Figure 19: Example of a classical TETRIS configuration consisting of an L on top of a J.

Consider a simple configuration like the one in Figure 19. In the classical game, this configuration can be reached in two moves. The question that needs to be answered is whether this configuration can be reached in an arbitrary quantum version where only superpositions of discrete pieces are allowed, regardless of the type of pieces used. It is sensible to try to manipulate the superposition age numbers in order to determine if such a configuration is reachable. Although the pieces of a superposition could theoretically mimic any arrangement of classical pieces since they can rotate and shift in different positions, achieving every possible configuration of the classical game might be practically infeasible due to the large number of potential configurations of the quantum version and the age limitation. For instance, if we assume that each superposition is generated with an age equal to 100, it would be significantly complex to track all superpositions and ensure whether their collapse leads to a classical configuration. As the game progresses and more pieces are added to the grid, the computational complexity increases exponentially which means that a significant amount of resources is required in order to manipulate quantum superpositions. Thus, if computational constraints are taken into account, achieving all classical configurations in a QUANTUM TETRIS mode would be highly challenging. Note that, for the remainder of this section, we will be focusing on a 7-wide grid for constructing configurations, which is a reasonable choice in terms of placing 3-wide or 4-width tetrominoes next to each other.
Now, it would be interesting to investigate whether a classical configuration like the one in Figure 19 would be possible to appear in the quantum game if we neglect any kind of computational restriction and assume that we can manipulate the piece selection. Consider an *empty* TETRIS grid with seven columns and arbitrarily many rows. It is clear that this state can be reached in zero moves. Another way to reach this configuration is to vertically place an I-piece next to three pairs of O-pieces (see Figure 20). Therefore, we have found a game instance where reaching the same configuration in more than one way is possible.

In other words, not all TETRIS configurations are uniquely constructed. We now want to determine whether following the same technique would work for non-empty configurations or not, especially in examples like the one in Figure 19 with a non-flat horizon (meaning that there are empty cells in the top row).

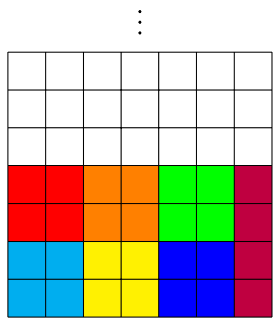
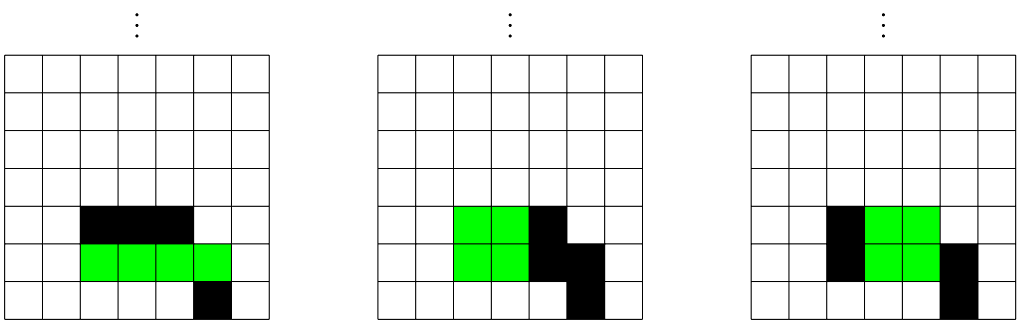


Figure 20: Example of a configuration equivalent to an empty grid.



(a) (b) (c)

Figure 21: Classical pieces cannot be used to reproduce the L-J configuration.

It is trivial to prove that if the configuration in Figure 19 is constructed without any row clearances occurring, the combination of pieces used is unique. To prove this, we will try to fit different piece pairs in the (red and blue) occupied cells in the figure. First of all, Figure 21 shows that classical I and O cannot be used in any combination since black cells still need to be filled by a tetromino or a superposition; we assume that game gravity applies and therefore, in (b), the O-piece is not allowed to float. Moreover, all bounding box superpositions consist of either five or six cells (see Figure 6), which means that, if a superposition is used, the remaining three or two cells must be filled by another piece, which is impossible since all pieces consist of four cells. Therefore, the only way to construct the configuration in Figure 19 in two moves is by using an L-piece and a J-piece.

As mentioned above, it would be extremely complex to predict all possible QUANTUM TETRIS configurations. Using the 7-wide grid, we could focus on the bottom line and determine which configurations or occupations can be reached. Considering that we have 7 cells in each line and, since a cell can be either filled or empty, there can be $2^7 = 128$ occupations of the bottom line. By excluding the full row and empty row scenarios we have 126 different occupations. Specifically, the occupations of one filled cell are seven in total, if we also include the symmetrical cases, and they are all constructible. The first three rows can be filled with a J, T or L respectively, along with an I placed horizontally. The last three rows are constructed symmetrically (see Figure 22). The middle row can be constructed with a combination of L, J, T and O's (see Figure 23).

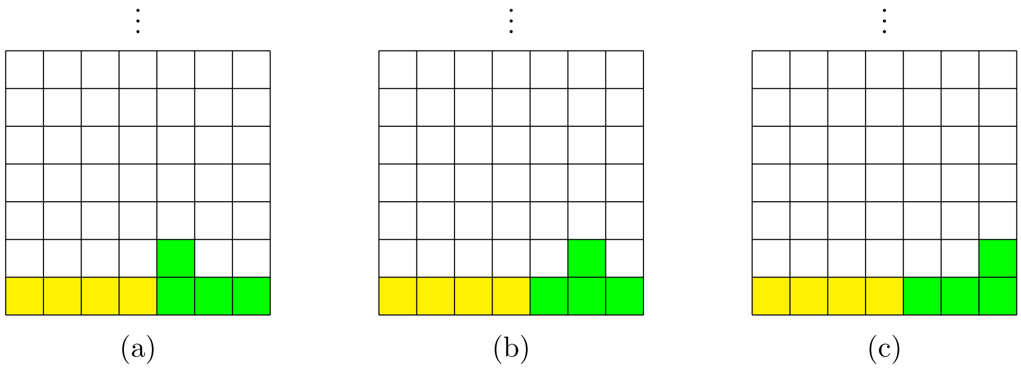
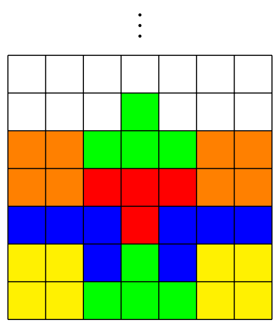


Figure 22: Examples of a single cell occupation of the bottom line after a row clearance. In all configurations, the superposition (green) is placed first and collapses after the classical piece (yellow) is placed.



(a)

Figure 23: Example occupation of the middle cell of the bottom line after five row clearances.

Regarding occupations with two or more (up to six) cells of the bottom line, we aim to find a general rule to construct them. Some two-cell occupations can be created directly from one-cell occupations (see Figure 24a and g). In total, we have $\binom{7}{2} = 21$ two-cell occupations and 9 of them are symmetrical with respect to the middle column, therefore we have to construct 12 configurations in total. Figure 24 shows ways of constructing all two-cell occupations of the bottom line. Note that, in all cases, the order of placing the pieces is important; we assume that superpositions are generated with an age equal to two. We start with a superposition and we alternate between superpositions and classical pieces to ensure that all superpositions are collapsed in the final round. It is clear that all configurations are reached after two row clearances, except from (j) which requires six row clearances. All these configurations include $2 \times 7 + 2 = 16$ occupied cells, or four pieces before clearance. Following a similar strategy, we assume that three-cell occupations will require at least three row clearances, or $3 \times 7 + 3 = 24$ occupied cells, or six pieces. Again, the last piece placed in the grid must be classical to ensure that superpositions are collapsed beforehand. An example of a three-cell occupation is depicted in Figure 25.

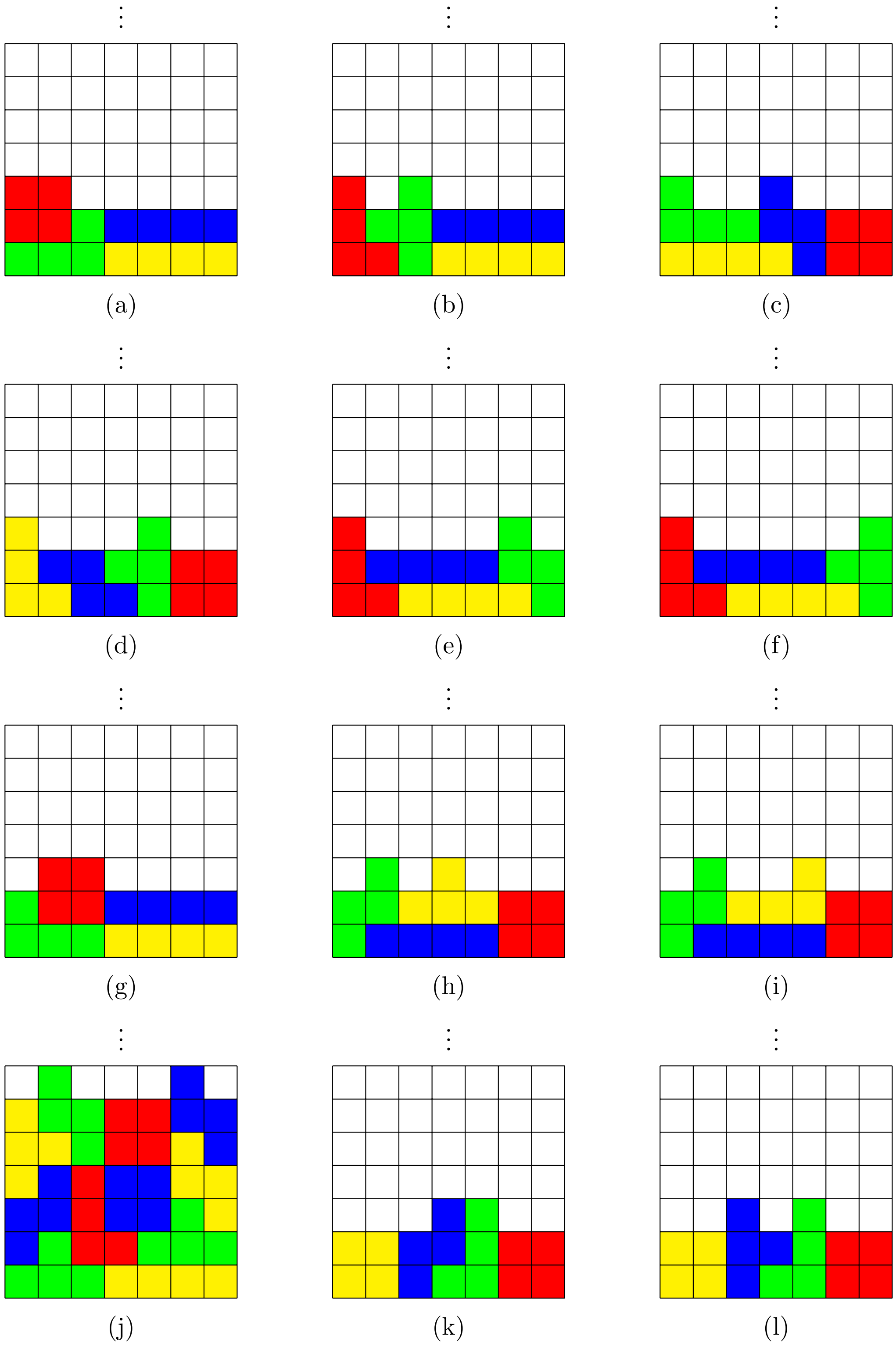
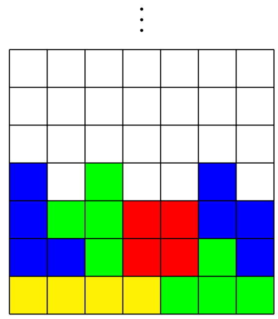


Figure 24: Examples of constructing all two-cell occupations of the bottom line. All constructions start with a superposition and end with a classical piece to ensure collapse.

The constructions in Figures 24 and 25 confirm the following strategy. When we have a grid of width 7, every row clearance removes 7 occupied cells from the grid and every new piece adds 4 (when collapsed). Therefore, excluding the exceptions, one row clearance leads to a

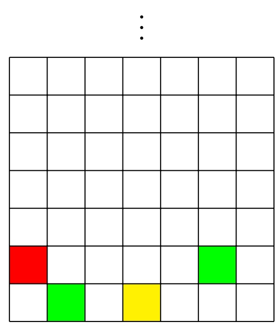


(a)

Figure 25: Example of a three cell occupation of the bottom line.

one-cell configuration, two row clearances lead to a two-cell configuration, and so on. In every case, we can see the stack of rows to be cleared as a platform that helps build a configuration, and the remaining cells as an overflow [14].

A general proof of the constructibility of every classical configuration could be reached by combining the one-cell and two-cell configurations constructed above, and the construction from [14]. Starting with an instance from Figures 22, 23 or 24, which we have already constructed, we can build a platform with pieces to prepare for the next piece placement. Then, we can create the next row by forcing row clearances after placing superpositions and classical pieces alternately. For example, consider Figure 24(h) to be the initial configuration. By constructing the configuration in Figure 24(e) on top of it we have built a second row (see Figure 26). We can potentially produce a classical configuration by combining one-cell or two-cell configurations in a similar way. This conjecture is left as future work.



(a)

Figure 26: Creating a configuration by combining configurations from Figure 24.

Returning to the L-J configuration of Figure 19, we will show that, assuming arbitrarily many moves and row clearances are allowed and all superpositions are generated with an age equal to two, there exists more than one way to reach the same configuration. This can be easily seen in Figure 27. In this instance, we reproduce the L-J configuration in nine moves and after four row clearances, based on the platform-overflow strategy explained earlier. The main strategy behind the construction is that, since we considered a 7-wide grid, a row clearance implies that seven cells are cleared at a time and, therefore, we can use a combination of the classical I-piece and a bounding box superposition in order to manipulate the remaining cells. Taking that into account, along with the fact that every superposition collapses into a 4-cell piece, the sequence of occupied cells in every round is as follows:

$$
\begin{aligned}
&4,\\
4+4-7&=1,\\
1+4&=5,\\
5+4&=9,\\
9+4-7&=6,\\
6+4&=10,\\
10+4-7&=7,\\
7+4&=11,\\
11+4-7&=8.
\end{aligned}
$$

Note that the same technique cannot be used for a 5-wide or 6-wide grid because the row clearance rules differ. Investigating if a classical configuration is constructible in a QUANTUM TETRIS game with a grid with less than 7 columns remains open.

As mentioned above, considering a fixed-age quantum version with large superposition age numbers would bring significant limitations when leveraging pieces to construct TETRIS configurations equivalent to classical ones. However, we showed that it is possible to construct classical TETRIS configurations in a QUANTUM TETRIS instance that allows bounding box superpositions of age 2, classical I and O, a 7-wide grid and "naive" gravity.

We will now examine the most intuitive case. Consider a minimal-age quantum scenario, where superpositions collapse at the end of the round after being positioned in the grid, and the traditional game gravity applies. This scenario can generate the L-J configuration in Figure 19 in 16 possible ways; by combining the four possible J-piece superpositions (Figure 28) with the four possible L-piece superpositions (Figure 29) and rotating accordingly, the collapse in any of these scenarios will lead to the desired configuration. In conclusion, if all pieces are manipulated accordingly, we could potentially reach all classical configurations in a minimal-age quantum version of TETRIS where the collapse occurs immediately and this could happen in multiple ways depending on the superposition combinations of each piece in the classical configuration.

We summarize our findings in the following lemmas.

Lemma 1. *Regardless of the grid size, classical* TETRIS *is equivalent to a minimal-age* QUANTUM TETRIS *instance where the following hold:*

1. *Only bounding box superpositions are allowed,*
2. *I and O are played classically,*
3. *The age of every superposition is equal to 1 (minimal),*
4. *Traditional game gravity is applied.*

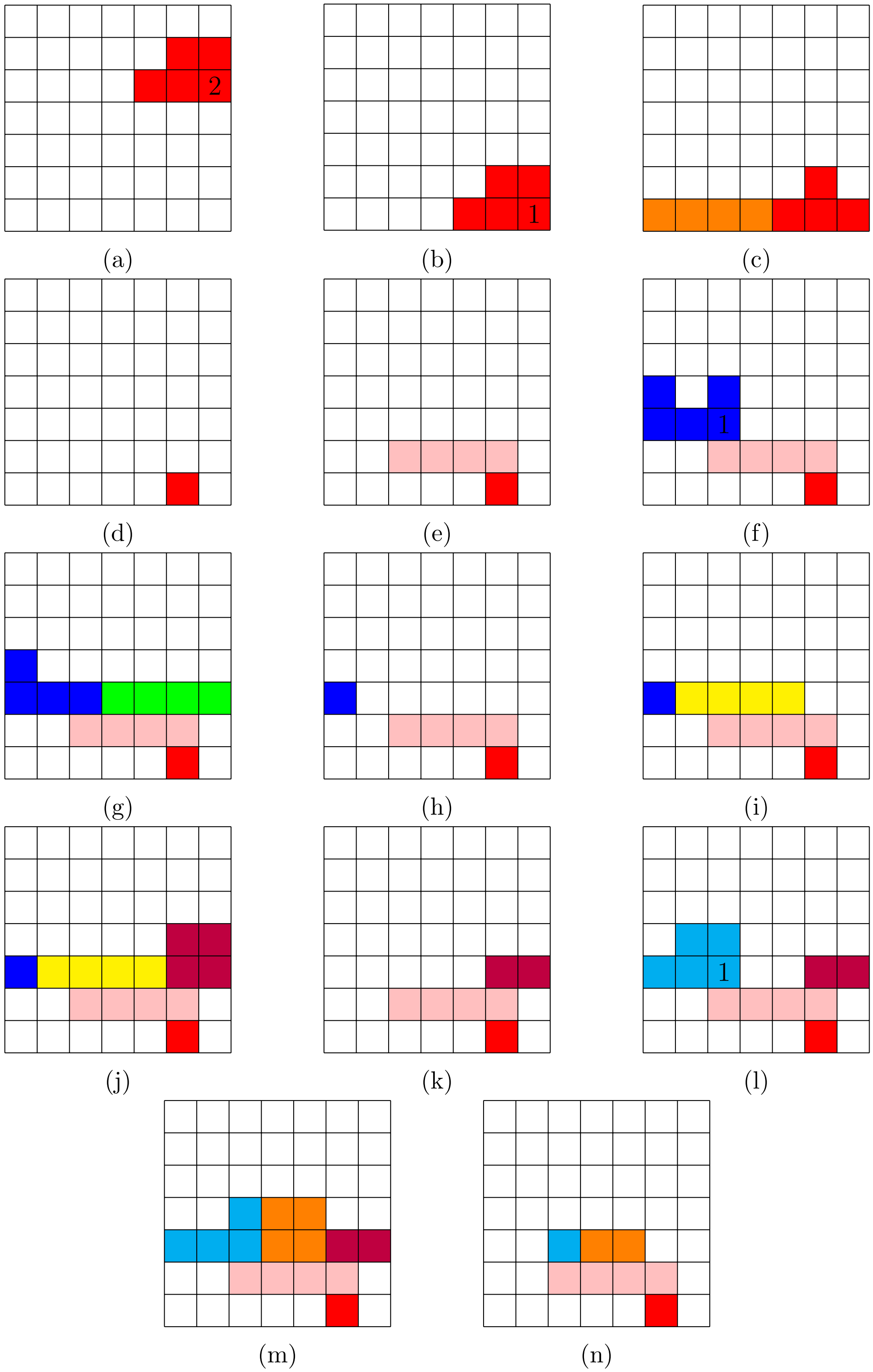


Figure 27: Another way to construct the L-J configuration. The last piece placed must always be classical (the O-piece in this case) to make sure that the second to last piece is collapsed.

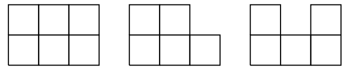


Figure 28: Possible superpositions of the J piece; J and S, J and Z or J and T, J and L respectively.

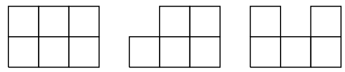


Figure 29: Possible superpositions of the L piece; L and Z, L and S or L and T, L and J respectively.

Lemma 2. *In a* QUANTUM TETRIS *instance where superpositions are generated with an age of two and classical I and O can be used, all one-line configurations with one or two cells are constructible.*

Lemma 1 essentially implies that *every* configuration in classical TETRIS is constructible in a minimal-age QUANTUM TETRIS game instance similar to the one we implemented, and vice versa. It is straightforward that, immediately after a superposition's collapse, the now classical piece behaves the same way as in the classical game, since its state is final and cannot be modified.

Lemma 2 summarizes our findings from Figures 22, 23 and 24. These configurations can essentially be used as an auxiliary platform to build one extra row at a time and end up with a desired configuration.

7 Research Method

A survey was conducted in order to collect data and feedback for all four versions of the game; classical TETRIS, minimal-age QUANTUM TETRIS, fixed-age QUANTUM TETRIS with the default age of three, and entangled QUANTUM TETRIS. A questionnaire was created for this purpose, which consists of four parts; players' background, engagement, gameplay strategies and general feedback. The first part collects information about the players' familiarity with video games, classical TETRIS and Quantum Computing. The second and third parts focus on answering the first and second research questions respectively; We are interested in knowing the effects of Quantum Mechanics on player engagement in the game, as well as the emerging gameplay strategies in the three different QUANTUM TETRIS variations we developed. The fourth part gathers general feedback about the game's design and functionality.

7.1 Participants

We invited 20 students of various academic and gaming backgrounds to play the game and participate in the survey. We care about comparing players' performance and finding relations with their knowledge of Quantum Computing or their gaming experience. Players were asked to try each game version once, after being reminded of the rules of classical TETRIS and instructed on what kind of mechanics to expect in all three QUANTUM TETRIS versions. Their scores for each version were collected for statistical purposes; aside from investigating differences in emerging strategies (qualitative analysis), we are interested in comparing players' performance in the different quantum versions and the classical version (quantitative analysis).

7.2 Procedure

Players were asked to try each version of the game once in order to document their first impression results. The quantum game rules were presented to them so they have an idea of what to expect during gameplay. After that, they completed a brief questionnaire which can be found in Appendix A. The questionnaire aimed to gather information regarding the overall engagement of the quantum-inspired aspects and the emerging strategies in the three quantum versions, all combined with players' backgrounds in Quantum Computing and games. Participants were asked to rate the enjoyment and the perceived difficulty of each version of QUANTUM TETRIS on a scale from one to five, compared to the classical game. Their scores for each version were also recorded; every player was allowed to play each game version once. Furthermore, they reported how the introduction of quantum-inspired mechanics influenced their gameplay experience and the strategies they adopted for the game through some open questions. The procedural approach maintained consistency among the participants since they were asked to play the game individually on the same computer without any distractions or information about leveraging quantum features.

7.3 Results

We will present two kinds of results stemming from the questionnaire; quantitative results, which include player performance comparison and game score visualization for both the classical game and the quantum versions, and qualitative results, which include analysis of gameplay strategies and the influence of the quantum-inspired mechanics in gameplay. Finally, we will answer the two research questions raised in Section 1.3.

7.3.1 Quantitative Results

After the in-game data collection from each game version, the most noticeable result is the large range difference between the classical and quantum scores. The score ranges for Classical Tetris, Minimal-Age, fixed-age and Entangled Quantum Tetris can be seen in Figure 30; it shows clearly that the ranges are progressively decreasing. Recall from Section 5 that players can clear up to four rows simultaneously and gain 100, 300, 500 or 800 points in all four game versions.

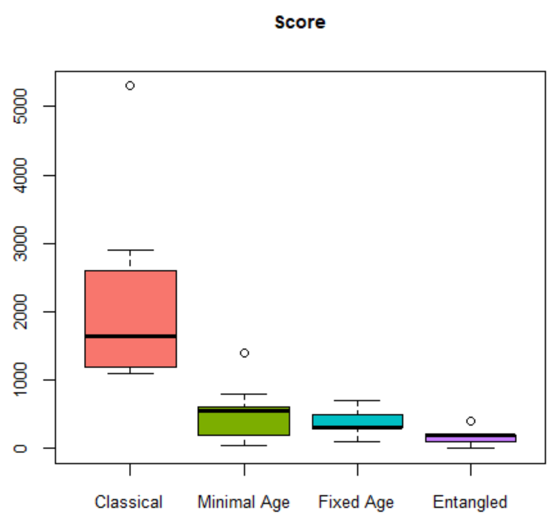


Figure 30: Players' scores in Classical Tetris, Minimal-Age, Fixed-Age and Entangled Quantum Tetris.

In the classical game, 50% of the participants' scores range from 1200 to 2600, with a median of 1600. No players scored lower than 1100 points. Finally, there is one outlier that scored 5300 points. In Quantum Tetris, scores are significantly lower. Starting with the minimal-age version, 50% of the scores range from 400 to 800 with a median of 600. An outlier is met at 1400 points, which is 600 points higher than the next highest score. In the fixed-age version, the score range is even smaller; 100% of the scores are met in the interval from 100 to 700 points. The median is 300 points and there are no outliers. Finally, the smallest range is seen in the entangled Tetris version, with scores from 0 to 200 points for all players and an outlier of 400 points. Summarizing, players' performance is, in a sense, degraded as the use of Quantum Mechanics gets more complex in the quantum versions.

As mentioned earlier, we are interested to know how players perceive the difficulty of Quantum Mechanics in the game and how that actually reflects in their scores, all that in comparison with players' familiarity with Quantum Computing Theory. Each subfigure in Figures 31 and 32 depicts participants' familiarity with Quantum Mechanics versus their perceived difficulty and their actual scores in each quantum version (minimal-age, fixed-age, entangled) respectively.

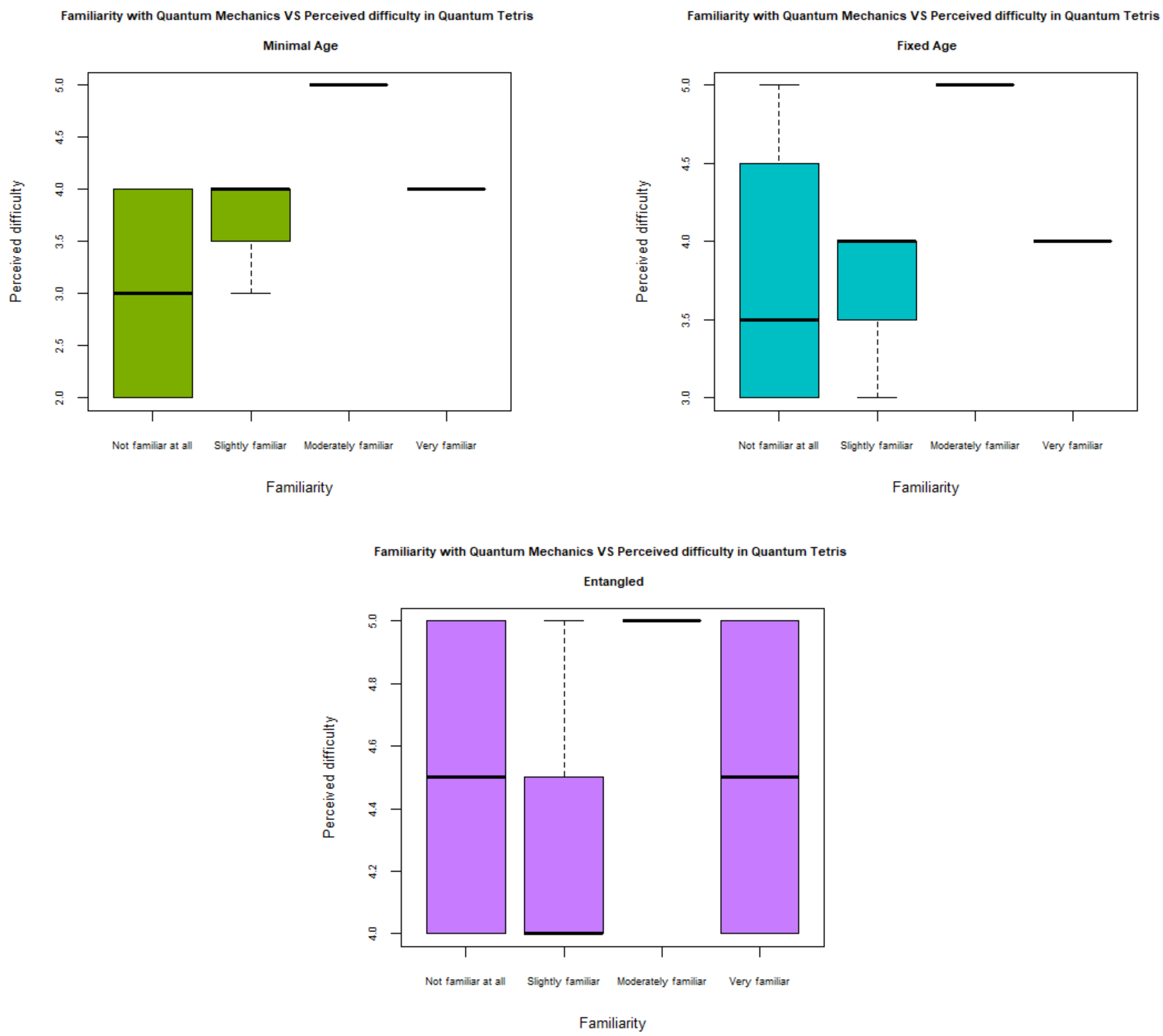


Figure 31: Players' familiarity with Quantum Mechanics vs players' perceived difficulty of the QUANTUM TETRIS versions.

In Figure 31, the perceived difficulty is rated from 1 to 5; 1 is interpreted as the game version being much easier and 5 as being much harder than classical TETRIS. Results vary among the three quantum versions. However, all players claim that the addition of Quantum Mechanics made the classical game more difficult since the median is equal to or higher than 3 in all versions and all familiarity levels. It is worth mentioning that, in the minimal and fixed-age versions, quantum unfamiliar players perceived, on average, lower difficulty than the quantum familiar players. Specifically, in both versions, all "moderately familiar" players rated the game difficulty as 5, and all "very familiar" players as 4. In the entangled version, which is considered to be the most challenging quantum version, results are more homogenous since players agree on a perceived difficulty between 4 and 5. Overall, players' familiarity with Quantum Theory does not seem to be proportional to their perceived difficulty in QUANTUM TETRIS.
Figure 32 shows the participants' scores in each quantum version compared to their claimed familiarity with Quantum Mechanics. In the minimal and fixed-age versions, quantum unfamiliar players scored, on average, less than slightly, moderately or very familiar players, with medians equal to 180 and 250 respectively. A remarkable result is that the outlier in the minimal-age

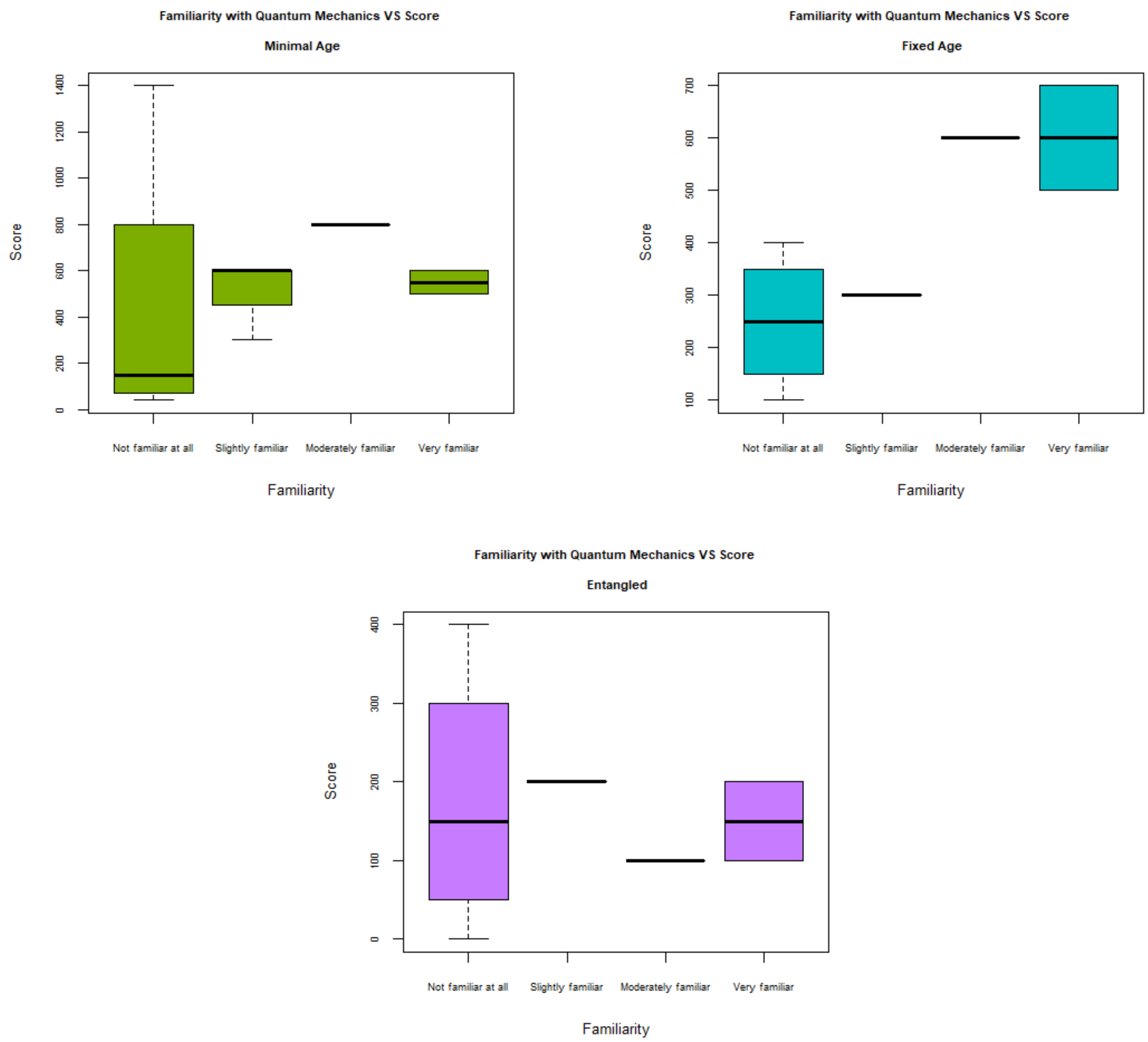


Figure 32: Players' familiarity with Quantum Mechanics vs players' scores in the Quantum Tetris versions.

version is a quantum unfamiliar player. The fixed-age version shows clearly that moderately or very familiar players scored the most points, almost double the points of unfamiliar or slightly familiar players on average. Finally, the entangled version's outlier of 400 points is also met in the quantum unfamiliar player category. Surprisingly, quantum unfamiliar players show the largest fluctuation in scores and some of them have scored even higher than all quantum familiar players. Summarizing the results, there is not enough evidence to claim that familiarity with Quantum Mechanics is proportional to the quantum game scores since there is no consistency between performance and players' knowledge in the field.

7.3.2 Qualitative Results

As mentioned earlier, the qualitative data collection focused on investigating players' perception of Quantum Mechanics in the game and assessing how they affected the strategies they developed to leverage them. We will interpret the qualitative results based on participants' answers to the open-ended questions in the questionnaire.

Regarding the quantum-inspired mechanic perception, all participants agreed on the quantum versions' uncertainty and unpredictability, which resulted from the way the superpositions were defined. Specifically, 85% of the players associated the game uncertainty with a more challenging gameplay and emphasized the difficulty of scoring many points. Many participants claimed that the main challenge in QUANTUM TETRIS lies in the risk that needs to be taken because of the combination of unpredictable pieces and the limited time to make a move. In other words, they found it complex to calculate optimal moves in every round. The rest of the players associated the superposition uncertainty with creativity. According to them, quantum-inspired mechanics are considered to introduce new rules in the game and they turn it into a new, in a sense, different game where the way of stacking, sliding or rotating pieces varies and requires creative thinking. For this portion of participants, the game appeared to be more interesting and engaging. Overall, to answer the first research question, players perceive quantum-inspired mechanics differently and take into account different criteria for measuring game engagement. As discussed in Section 7.3.1, there is no direct connection between players' familiarity with Quantum Mechanics and their performance in the quantum versions, since there are multiple examples of quantum unfamiliar players who scored higher than quantum familiar players. Therefore, players' experience and engagement depend solely on the gameplay and the randomness it encounters every time, rather than the quantum background and the "quantumness" of each game version.

Regarding the emerging strategies and decision-making processes, 80% of the participants adopted different strategies in all versions of QUANTUM TETRIS than the one they used in classical TETRIS. In order to score more points in the game, most of them focused on utilizing the information they had on how superpositions and entanglements work in the game, rather than following strategies based on classical TETRIS rules; rather than building large structures out of pieces to clear multiple rows simultaneously, they focused on the randomness factor stemming from the collapse of superpositions, and compromised with clearing a single row if possible, since the collapse results are out of players' control. Another popular strategy among participants was alternating between stacking quantum pieces on the sides and classical pieces in the middle, and vice versa. However, this strategy did not seem to be effective long-term in the quantum game, because players had to deal with stricter time limitations and a continuously denser game grid. Finally, a significant portion of the participants (45%) stated that, to a large extent, their decisions in the quantum game aimed at "filling the gaps" in the grid. Again, such a strategy contains the randomness factor due to the collapse of superpositions. Overall, to answer the second research question, it is fair to say that players' strategies in classical and quantum-inspired TETRIS differ; the superpositions' unpredictability is the main element considered in their decision-making processes and they face this by adopting "safe" strategies, even if that yields a very slight improvement in their scores. A proportion of the participants were "forced" to develop new strategies in order to handle the quantum-inspired game mechanics.

To conclude the results, we quote some of the most remarkable comments from the participants about the game elements and the overall gameplay experience:

"... the superposition element was interesting ..."
"... I liked the game design and colors ... "
"... the entangled version was confusing ... "
" ... I would slow down the game to have more time to think ...
"... the superposition pieces of the current round should be displayed ..."

8 Conclusion and Future Work

In this thesis, we developed a QUANTUM TETRIS version that simulates Quantum Mechanics in the classical game TETRIS. Contrary to other quantum game approaches, we implemented a simple QUANTUM TETRIS game in Python without using any Quantum Computing libraries or frameworks. In order to maintain a simple game logic and encourage players to test their abilities regardless of their Quantum Computing knowledge, we defined two concepts to assist in implementing superpositions and, consequently, entanglements; bounding box and piece aging. The bounding box rule allows the generation of superpositions consisting of two tetrominoes that fit in a 2×3 bounding box, and the aging rule assigns an integer number to every superposition to indicate the moment of its collapse. We distinguished three quantum categories in the game; minimal-age QUANTUM TETRIS where every superposition collapses immediately after being placed in the grid, fixed-age QUANTUM TETRIS with age equal to three where a superposition always collapses after three rounds, and entangled QUANTUM TETRIS where two identical and codependent superpositions are generated at a time, affecting each other's final outcome after collapse. Moreover, we claimed that a minimal-age QUANTUM TETRIS instance is equivalent to the classical game because of the similarities in the behavior of tetrominoes, and defined a quantum instance where classical configurations are constructible. Moving on to the research method, we defined two research questions and conducted a survey with 20 participants to explore players' perception of Quantum Mechanics in the game and the strategies they employ to manipulate quantum features. The key finding was that, regardless of players' gaming background or knowledge of Quantum Computing, the number of quantum features ("quantumness") in the game is inversely analogous to players' performance. This results from players following different decision-making processes that focus on leveraging quantum features and unpredictability.

Several limitations and weaknesses must be acknowledged in this work. First of all, the large state space of classical TETRIS restrained this study's scope to specific instances and configurations. Combining this with the probabilistic nature of Quantum Mechanics posed challenges in reproducing outcomes and conducting a broad comparative analysis. Regarding the considerations in the game implementation and design, the main obstacle was the inability to follow methods used in developing quantum combinatorial games for our own game, since TETRIS cannot be seen as a combinatorial game; it is, in principle, a single-player game with no perfect information, a time limit for every move and the moment it ends is not predetermined. Furthermore, multiple technical matters needed to be considered in the design, such as selecting between traditional or "naive" gravity and ensuring that a row clearance never precedes a collapse.

8.1 Future Work

The current game version could be extended and enhanced in multiple ways. First, increasing the element of randomness by generating pieces with undefined or unknown ages would be of great interest. Moreover, modifying the fixed-age version by implementing traditional game gravity could lead to different strategies and performance results. In our implementation, we chose among some scenarios defined in Section 4 to base our study, but the rest of the superposition and entanglement scenarios remain unexplored. Finally, there are some unanswered questions regarding the equivalence between classical and QUANTUM TETRIS; for example, finding the minimum number of conditions that must hold in order to claim that configurations between the classical game and a quantum instance are equivalent. Experimenting with large grid sizes and allowing superpositions of all seven tetrominoes to eliminate classical behavior would be a reasonable continuation of the current study. Moreover, the problem of constructing every classical TETRIS configuration by creating a platform and stacking one-cell and two-cell configurations, which we have already proved to be constructible, remains open.

Beyond gaming and entertainment purposes, the current thesis could serve as an educational tool for Quantum Mechanics since the implementation introduces players to quantum concepts through gameplay mechanics. Making Quantum Computing concepts accessible to everyone through a familiar game can raise awareness and interest in the field. Furthermore, the existence of quantum-inspired mechanics in the game is expected to enhance logical thinking and strategic planning since players need to develop efficient strategies to handle the quantum aspects of the game. Aside from monitoring player's performance in the game, future research may include simulating basic quantum algorithms to identify challenges and propose solutions to optimize gameplay.

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A Appendix: Questionnaire

Background

How often do you play video games?

- ◯ Daily
- ◯ Weekly
- ◯ Monthly
- ◯ Rarely
- ◯ Never

How familiar are you with classical *Tetris* gameplay mechanics?

- ◯ Not familiar at all
- ◯ Slightly familiar
- ◯ Moderately familiar
- ◯ Very familiar
- ◯ Extremely familiar

How familiar are you with Quantum Computing/Quantum Mechanics?

- ◯ Not familiar at all
- ◯ Slightly familiar
- ◯ Moderately familiar
- ◯ Very familiar
- ◯ Extremely familiar

Engagement

How did you find the overall enjoyment of each version of *Quantum Tetris* compared to classical *Tetris*? (1 being much less enjoyable, 5 being much more enjoyable)

	1	2	3	4	5
Minimal Age	◯	◯	◯	◯	◯
Fixed Age	◯	◯	◯	◯	◯
Entangled	◯	◯	◯	◯	◯

Rate the perceived difficulty of each version of *Quantum Tetris* compared to classical *Tetris* (1 being much easier, 5 being much harder)

	1	2	3	4	5
Minimal Age	◯	◯	◯	◯	◯
Fixed Age	◯	◯	◯	◯	◯
Entangled	◯	◯	◯	◯	◯

Gameplay Strategies

How did the introduction of Quantum Mechanics (superpositions, entanglements) influence your gameplay experience?

Did you adopt different strategies in *Quantum Tetris* compared to classical *Tetris* to leverage quantum features? If yes, describe what you did differently.

- ○ Yes
- ○ No

General Feedback

Overall, what did you like and dislike about the game? What kind of changes would you make?