Impact of Quantum Mechanics-Based Workshops on Developing High School Students' Interest and Intuition in Quantum Information Science

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Abstract - **Our research aims to analyze the impact of quantum mechanics-themed games on the development of high school students' intuition and interest in topics related to quantum phenomena, such as quantum superposition and quantum measurement. In the United States, quantum concepts are introduced at a fragmented level in high schools, and efforts to implement a quantum curriculum at the secondary level have been limited. This presentation describes the development of a workshop, and the associated research study, scheduled for implementation in the late winter and spring of 2024. The workshop utilizes an interactive game-play method to introduce students to concepts in quantum computing. We anticipate that this workshop-based pedagogical approach will enhance students' ability to connect intuitive and non-intuitive concepts in QISE (Quantum Information Science and Engineering) from their experience of playing the game. We hypothesize that enabling high school students to interact with quantum mechanics concepts during their secondary education will foster sustained interest and potentially encourage them to pursue further studies in the field of QISE.**

Index Terms – Quantum Information Science and Engineering (QISE), Quantum Chess, Pre-College STEM Education.

INTRODUCTION

The field of quantum information science and engineering has been evolving rapidly over the past few decades. Quantum computers have revolutionized the efficiency and speed at which we can solve challenging computational tasks in physical sciences and engineering [1], [2], [3]. Although there have been several efforts to generate a larger quantum-efficient workforce in higher education, efforts to promote quantum science at the high school level have been rather limited. Although high schools around the world have started to incorporate quantum concepts at a fragmented level [4], these curricula often neglect key QISE concepts. For example, quantum entanglement, which plays a significant role in QISE, has only been introduced in the curriculum for 2 out of the 15 countries [5].

Introducing QISE concepts at the high school level can be a significant challenge. Studies have shown that high school students often tend to confuse classical and quantum descriptions of the physical world, making it difficult for them to gain a better understanding of non-intuitive concepts like superposition, entanglement, and probabilistic measurement [6]. As a result, identifying better pedagogical approaches for teaching these core concepts is an active area of research [5], [6], [7]. Quantum games typically involve these types of concepts, and thus are promising pedagogical tools that have direct application to QISE.[8], [9], [10], [11] Despite their promise for introducing the rather "non-intuitive" aspects of quantum mechanics, there have been few studies investigating the actual effect of quantum-based games on student learning outcomes and/or student perceptions [12], [13]. Thus, the knowledge gained from our research effort will address a significant gap in the QISE education literature.

GOALS OF THE STUDY

The primary goals of the study are three-fold:
1. Investigate the effect of interactions with quantum-based games, e.g., Quantum Chess [14], on secondary students' understanding of quantum phenomena, such as superposition and non-deterministic measurement outcomes. Knowledge gained along this aim will contribute to the development of a theoretical framework for student conceptual understanding of quantum mechanics at the secondary level.
2. Evaluate student perceptions of how the various aspects of the workshop (lecture, demonstration, interactive games, and puzzles, etc.) contribute to their understanding of "non-intuitive" aspects of quantum mechanics, such as superposition and measurement. Knowledge gained along this aim will enable QISE educators to evaluate and improve methods for quantum mechanics instruction at the secondary level.
3. Evaluate student perceptions of how engagement with quantum-based games in secondary school influences the program of study they select in college. Knowledge gained

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along this aim will provide insights on methods for incorporating inclusive quantum mechanics education at the secondary level.

Prior Work At Yale Pathways

An earlier version of this workshop was carried out at Yale University via the Yale Pathways to Science program in late August 2023, where approximately 30 students with various demographic backgrounds from 10 different high schools in the counties New Haven, West Haven, and Orange (Connecticut) participated. The workshop included an introduction to the game of chess, specifically focusing on the large number of potential outcomes for the game. As the number of moves played during a chess game increases, the number of possible games increases exponentially so that even the most powerful supercomputers are incapable of finding the absolute best moves. The discussion of possible chess games motivated the presentation of quantum computers during the workshop, which introduced students to the quantum advantage recently illustrated in the literature [2], [3], [15], [16], [17], [18]. In understanding what quantum actually means - specifically the concepts of superposition and measurement - participating students familiarized themselves with Quantum Chess and were encouraged to try different puzzles. Inspired by the generally positive feedback received, we aimed to implement a similar workshop, with some revisions, to serve a broader audience of high school students. Our initial implementation of the revised workshop will be implemented at high schools in the Lehigh Valley during February, March, and April 2024.

Learning Outcomes

We expect that participating in the interactive workshop on Quantum Chess will expand participants' understanding of quantum science through guided play. By interacting with the chess pieces on a board, we hypothesize that students will begin to develop an intuition that will enable them to think about quantum superpositions and non-deterministic measurement outcomes. We also hypothesize that workshop participation may encourage students to pursue further study in QISE fields.

To measure student learning outcomes, pre- and post-workshop surveys asking about their understanding of wave-particle duality, quantum superposition, wavefunction collapse, and quantum measurement, will be provided to workshop participants. The short answer responses will be coded and analyzed for themes related to concepts that students either were or were not able to correctly describe. The comparison of the results from pre- and post-workshop surveys will enable us to understand the impact of the workshop on achieving the student learning outcomes. In the long term, we will survey workshop participants once per year to track their level of interest in QISE and their perceptions of how participation in the workshop did or did not contribute to their career path.

Structure of the Workshop

The workshop implementation in the Lehigh Valley this winter and spring (2024) will be structured as follows: First, students will complete a pre-workshop survey to determine their prior engagement and understanding of quantum mechanics concepts. They will then receive a brief introduction to quantum concepts and their applications in QISE, followed by an interactive tutorial on the Quantum Chess game and some time for students to explore Quantum Chess puzzles independently. Then facilitators will provide a more detailed explanation of superposition and non-deterministic measurement outcomes, after which students will engage in solving puzzles again and even playing chess with each other. The session will conclude with an exit survey to assess the level of understanding students have gained in quantum concepts through the workshop.

Timeline for Implementation

TABLE I
STUDY TIMELINE AND PROGRESS

Date	Milestone	Status
Summer 2023	Initial workshop implementation during Yale Summer Pathways Program	Completed
Fall 2023	Review feedback from initial implementation for workshop revision	Completed
Winter 2024	Finalize workshop preparation, administrative approval, and scheduling	In progress
Late Winter/ Spring 2024	Workshop implementation in high schools across the Lehigh Valley.	To be completed
Spring 2024	Data collection and analysis	To be completed
Summer/Fall 2024	Dissemination of results	To be completed
Fall/Winter 2024	Revisions to workshop for further implementation	To be completed

Quantum Chess

Our workshop utilizes the Quantum Chess game by Quantum Realm Games, a small company with a mission to spread knowledge of quantum phenomena through video games [11], [14]. As the name would suggest, quantum chess implements ideas crucial to quantum mechanics into the gameplay of chess. Through tutorials and multiple puzzles of increasing complexity, the game encourages users to think about various chess moves and scenarios differently, akin to how quantum mechanics challenges classical mechanics. After initially becoming acquainted with the "quantum aspects" of quantum chess, the game becomes a tool for users to gain confidence in their understanding of the various paradoxes and probabilities related to their quantum chess moves. Ultimately, the aim is to help participants to develop a "quantum intuition" that enables them to accept (and interpret) the distinctive phenomena inherent to quantum physics, upon their future encounter with the subject.

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SUPERPOSITION AND QUANTUM CHESS

In classical chess, each square has two states: it's either occupied (1) or unoccupied (0). In quantum chess, each square is represented by a qubit. If the qubit is in the $|1\rangle$ state, then the square is occupied, and if the qubit is in the $|0\rangle$ state, then the square is unoccupied. However, since quantum chess uses qubits instead of traditional binary bits, superposition of the states is possible. Therefore, at any point, the state of a 64-square chessboard can be defined as a 64-qubit system:

$$|\psi\rangle = \sum_i A_i \left|q_0^{(i)}, \ldots, q_{63}^{(i)}\right\rangle \quad (1)$$

Regarding gameplay, this implies that we can have the same piece at multiple locations on the same board simultaneously. The most common example of a quantum chess move that involves superposition is the "split" move. This means that we can move a single chess piece to two different target squares. This can be achieved by treating the chess board as a set of qubits. For example, by performing a $\sqrt{iSWAP}$ between the qubit representing the source square and the qubit representing first target square, an equal superposition between the source and the first target is created. Then an *iSWAP* is performed between the source and the second target square, creating an equal superposition between the two target squares.

MEASUREMENT AND QUANTUM CHESS

The measurement of an observable quantity for a quantum system can only yield the eigenvalues of that observable. When a quantum system is described by a superposition state, $|\Psi\rangle = \sum_{i=1}^{N} c_i|\phi_i\rangle$, where $|\phi_i\rangle$ is an eigenstate of the operator for the observable and c_i is the corresponding coefficient for that eigenstate in the superposition, then upon measurement, the state of the quantum system will "collapse" to one of the eigenstates, $|\phi_k\rangle$, with the probability $|c_k|^2$. In other words, the act of measurement changes the state of the quantum system.

In Quantum Chess, the occupancy of the chessboard is described by a 64-qubit system, as shown in (1). An important rule is only one chess piece can occupy each square, which means that during gameplay, a capture move corresponds to a measurement. For example, if the chessboard is in a uniform superposition state of two possible board layouts, then when a player attempts to move a piece onto a square that could be occupied by their opponent's chess piece in either of those layouts, a "measurement" must be carried out to determine whether the enemy piece already occupies that square. Likewise, if a player attempts to use a chess piece that is in a superposition to capture an enemy piece, then a measurement must be performed to determine whether the capture is successful.

A capture move is not guaranteed to be successful but rather depends on the probability describing the superposition of the piece performing the capture. For example, if a knight is in a uniform superposition of being at A3 and C3, then an attempt of the knight at C3 to capture an enemy piece at D5 will be successful only 50% of the time. If the knight is known for sure to only lie at C3, it can always capture an enemy piece at D5, which is consistent with a classical chess game. The non-deterministic aspect of the quantum measurement typically confuses students because even if the student carries out the correct moves, there is still a chance that they are not successful until after repeating the same moves a few more times.

PEDAGOGICAL EFFECTIVENESS OF THE WORKSHOP

We have designed our workshop to be pedagogically effective at the high school level. We use the Quantum Chess game to introduce concepts from the standard interpretation of quantum mechanics without the mathematically sophisticated formalism of quantum mechanics. The quantum chess game illustrates major concepts in the standard interpretation of quantum mechanics, such as the possibility that a quantum system is in an indeterminate superposition of states, and that this indeterminacy is resolved when a measurement is performed - yielding one or another state with a certain probability. The contrast to classical mechanics, where there is a clear ontology of point particles with definite position and momentum at all times, is made by distinguishing quantum chess from standard chess, where the pieces have well-defined positions independently of any measurement being performed. We expect that the quantum chess gameplay combined with the targeted instruction during the workshop will enable students to begin developing an intuition for interpreting quantum phenomena.

An additional pedagogical value of the workshop is its' emphasis on the way quantum concepts can be practically applied. The rules that govern Quantum Chess are based on actual quantum circuits [11], and thus the game can be used to simulate more complicated quantum phenomena such as entanglement. We hypothesize that by providing students a guided approach to exploring these phenomena, and to see them in practice in the (relatively) familiar setting of chess gameplay, we will enable the students to develop new strategies to solve problems.

LIMITATION OF CURRENT/FUTURE STUDY

Limitations of the current studies include the limited sample size and the transient nature of the workshop intervention. For instance, we will run our workshop at high schools located within the Lehigh Valley, which could make it difficult to generalize our results beyond that region. We are attempting to address this limitation by running the workshop at many different high schools throughout the region. The transient quality of our workshop intervention and data collection may also limit our study, since we are planning to obtain participant perceptions immediately before and after the workshop, and we will only survey the students intermittently after the workshop. For example, it will be difficult to gain information about how the

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participants' future interaction with QISE impacts our follow-up surveys. To address these issues, we have included both quantitative and qualitative response items in our surveys, which will enable us to triangulate our data to draw more robust conclusions.

We expect that as we move forward with our workshop implementation and related investigation, we will further develop and refine our research questions. We plan to use our results from the winter/spring 2024 implementation to revise the workshop for future implementation.

Conclusion

The cutting-edge nature of QISE is a double-edged sword: although QISE offers a significant quantum advantage, there is also a high barrier of entry in QISE fields. In most cases, students don't encounter quantum concepts until their upper-level college classes, and by that point, students with the potential to make important contributions in QISE might have already moved onto other STEM fields or may have left STEM altogether. Furthermore, even for those students who do pursue quantum mechanics, there is still a significant learning curve due to paradoxical and non-intuitive concepts in quantum mechanics. To overcome these challenges, we aim to improve the general infrastructure for QISE education. Our study aims to not only introduce quantum concepts at the secondary school level, but also to further our understanding of what a general QISE educational framework could look like in the future.

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