Entanglion: A Board Game for Teaching the Principles of Quantum Computing

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ABSTRACT
Educational games are a creative, enjoyable way for students to learn about technical concepts. We present Entanglion, a board game that aims to introduce the fundamental concepts of quantum computing – a highly technical domain – to students and enthusiasts of all ages. We describe our iterative design process and feedback from evaluations we conducted with students and professionals. Our playtesters gave positive feedback on our game, indicating it was engaging while simultaneously educational. We discuss a number of lessons we learned from our experience designing and evaluating a pedagogical game for a highly technical subject.

CCS Concepts
•**Social and professional topics** → **Computational thinking;** •**Human-centered computing** → *HCI design and evaluation methods;*

Author Keywords
Quantum computing education; Pedagogical tools; Game-based learning; Board game

INTRODUCTION
Computational thinking [36] is a thought process in which problems and solutions are formulated in ways that align with how computers work. Thinking computationally involves breaking down problems into smaller parts, thinking about solutions as sequences of ordered steps, and using abstraction to make generalizations [7]. This thought process is modeled after the operation of classical computers, which perform a concrete sequence of instructions on concrete bits of data. But, what if those bits are not so concrete after all?

Recently, many technological advances have been made in the field of quantum computing, maturing it from a wholly theoretical field into one burgeoning with real-world experiments. Publicly available quantum computers, advanced software simulators, and domain-specific programming languages and SDKs enable anyone around the world to experiment with quantum algorithms. Quantum computing has the potential to solve problems considered intractable for classical computers, such as NP-complete problems with exponential search spaces [26] or factoring large numbers [29, 30].

Thinking "quantum computationally" is quite different than classical computational thinking. It requires a deep understanding of the underlying linear algebraic *math* to understand how a quantum algorithm works. To understand the hardware implementation of a quantum computer requires a deep understanding of the *physics* as well.

While quantum computers are currently limited in their abilities, we believe they will soon be able to solve problems intractable for classical computers. We believe that now is the time to start training the first generation of "quantum native" programmers who are able to think "quantum computationally" and devise new quantum algorithms to solve problems in fields such as chemistry, optimization, finance, and AI.

As a step toward this goal, we sought to design an educational experience to expose students and enthusiasts to the world of quantum computing. Games are an effective means for education [32], which led us to the idea of creating a board game to teach fundamental principles of quantum computing.

We present Entanglion (a play on the word "entanglement"), a cooperative board game for two or more players. Entanglion is a technically-accurate simulation of a 2-qubit system and it introduces players to concepts including qubits, quantum states, quantum gates, superposition, entanglement, measurement, and error, as well as several of the hardware and software components that comprise a quantum computer.

In this paper, we describe our iterative design process and how we created a technically-accurate simulation with enjoyable game mechanics. In order to evaluate the quality of our game, we solicited feedback from two groups of playtesters: middle and high school students (8th and 12th grade) and industry professionals attending a quantum computing conference. We found that Entanglion was enjoyed, it was readily learned after a short description of the rules, and it conveyed difficult technical concepts in an enjoyable, unique way.

We have released Entanglion as an open source project [3], and we encourage educators, students, and board game enthusiasts alike to download and print the game materials to assemble and play their own game, as well as extend it with new rules and mechanics.

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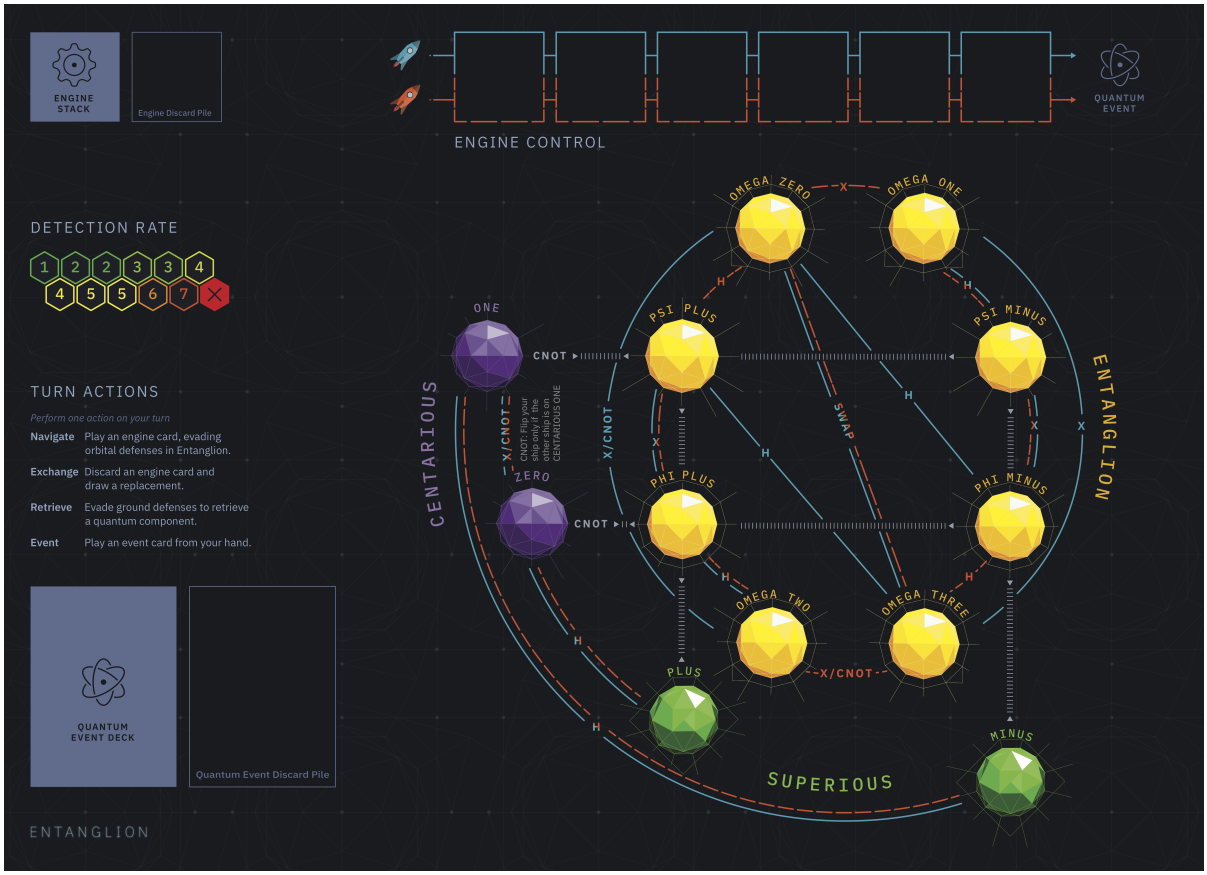


Figure 1. Entanglion: the world's first open source quantum computing board game.

RELATED WORK

Our decision to create a board game to teach principles of quantum computing was motivated by a wide range of prior work on using games to teach subjects as diverse as mathematics [35, 25], healthcare [12, 5], and climate change [11]. We opted to create a physical board game over a digital one to enable in-person collaborative experiences, especially in classrooms and other educational settings.

Educational Games

Games are effective teaching tools because they create situations of collaborative learning and positive interdependence [28]. Players collaborate with each other to learn and understand the game's mechanics, and hence the game's embedded concepts, in order to formulate a winning strategy.

Games have been developed for teaching principles of global software engineering [33] and for teaching medical students about the multidisciplinary nature of cancer treatment [12]. They have also been created to teach children about healthy eating [2], and about anatomy, diet, and risk factors for heart disease and cancer [5]. Games can even teach complex geopolitical topics such as climate change [11]. In some instances, these games have shown concrete learning or behavioral effects, such as a significant increase in nutrition knowledge and weekly vegetable intake [2] or an increased knowledge of invasive species [1].

Computational Thinking Games

Computer games have also been created to help players develop their computational thinking skills and encourage positive attitudes toward mathematical learning [20]. For example, Human Resource Machine [13] and Shenzhen I/O [4] teach the semantics of programming through puzzle-solving mechanics. Other games teach computational concepts such as data structures [22], formal verification of software programs [10], and parallel programming [34].

There are also several noteworthy games specifically about quantum. The Quantum Game [27] teaches quantum mechanics via physics-based puzzles. Quantum Tic-Tac-Toe [6] teaches concepts such as superposition and measurement, and Meqanic [23] has players manipulate quantum states using quantum gates. Quantum Moves [31] gamifies optimization problems in quantum physics, albeit with less emphasis on teaching quantum concepts.

Entanglion differs from other computational thinking games as it helps players build an understanding of quantum states and transitions between those states, rather than logic, data structures, or algorithms. It differs from other quantum games through its unique representation of quantum states its and collaborative learning process. We see Entanglion as contributing to an ecosystem of enjoyable educational experiences about quantum computing.

GAME DESIGN

We first give a brief summary of the actual game mechanics of Entanglion in order to provide a base for understanding our design goals and process. Next, we introduce several quantum computing concepts and discuss how they are embedded in the game. Then, we discuss our iterative design process and how the game evolved over time with feedback from subject matter experts.

Mechanics

Entanglion is a cooperative game for two (or more) players set in a sci-fi universe. Players must navigate two spaceships (red and blue) through the galaxies of Centarious and Superious to reach Entanglion in order to collect a set of eight quantum components to reassemble a quantum computer. The planets of Entanglion have defense mechanisms protecting those components. Upon arriving at a planet in Entanglion, players must evade the orbital defenses protecting it. If successful, they may then send an away team to the planet's surface to retrieve the quantum component; if not, their ships must quickly escape back to the safe harbor of Centarious. Away teams must also evade the ground defenses protecting the component. Quantum components grant new abilities or hindrances to players' ships, so they must strategize to collect them in an advantageous order. Players win the game after collecting all eight components; players lose if they are detected by orbital or ground defense mechanisms too much, as tracked by the "detection rate."

Each spaceship is controlled by one player, and players take turns using their own engine cards (shown in Figure 2) to navigate their ship(s) throughout the quantum universe. When ships are in Entanglion (the state of entanglement), the two ships always travel together. Navigation paths on the game board (shown in Figure 1) show how engine cards direct the movement of the ships. In some cases, only one color of ship may traverse a navigation path, and some paths may be traversed with multiple engine cards.



Figure 2. Engine cards are used to navigate ships around the quantum universe. Navigation paths on the game board are labeled with the card(s) needed to traverse them. These cards model actual quantum gates used to program quantum computers.

A "quantum event" is triggered after players have placed six engine cards. These events add an element of randomness to the game; sometimes, the event is beneficial for players, and sometimes it is not. Each quantum event is loosely modeled after an actual quantum-mechanical effect, or a person who made significant contributions to the field of physics or quantum information science, in order to expose students to these topics and encourage further learning.

A Board Game Model of Quantum Computing

We describe the fundamental quantum computing concepts modeled in Entanglion.

Qubits, quantum states, and quantum gates. Qubits are the building blocks of quantum computation. Qubits exist in a *state*, such as a classical state (0 or 1), a state of superposition, or a state of entanglement. In superposition, qubits have a probability of being observed as either a 0 or a 1 when they are measured. When two qubits are entangled, knowing the state of one qubit tells you the state of the other. Qubit states are manipulated using quantum gates; for example, applying the Hadamard (H) gate to a qubit in a classical state puts it into a state of superposition (and vica versa).

In Entanglion, each spaceship represents a single qubit and is controlled by one player. Players take turns using their engine cards to navigate their ship(s) throughout the quantum universe; when the ships are in Entanglion, they always travel together because entangled qubits always share the same state. The engine cards are based on actual quantum gates – X, Controlled Not (CNOT), Hadamard (H), and SWAP – and they are placed in an "engine control" space that represents a quantum circuit. Planets in the quantum universe represent the different quantum states achievable from our set of engine cards, and navigation paths depict how engine cards transition a spaceship (qubit) from one planet (state) to another. Planets are named after actual quantum states: the planets of Centarious (classical states) are Zero and One, the planets of Superious (superposition states) are Plus and Minus, and the planets of Entanglion (entanglement states) are Phi Plus, Phi Minus, Psi Plus, Psi Minus (known as the Bell states [14]), as well as Omega Zero through Omega Three (which do not have common names).

Measurement and error. Measurement is the process by which a qubit's state is *observed*. It collapses a quantum state to produce a classical value of 0 or 1. Measurement is a fundamental part of programming a quantum system; qubits are put into a "magical" state via the application of quantum gates, and only by measuring do we know the "actual" result.

Measurement is modeled via planetary defenses and the detection rate. When players navigate to a planet in Entanglion, they encounter orbital defenses and must roll the 8-sided Entanglion die to determine whether their ships have evaded the defenses (when their roll is greater than the current detection rate), or if their ships were detected (when their roll is less than or equal to the current detection rate). When detected, players are forced to make a quick exit by jumping back to a random planet in Centarious. This process is akin to performing a measurement on an entangled quantum state. In a real-world context, when a measurement is successful, the quantum state collapses to a classical state of 0 or 1. In game mechanics, a successful measurement is akin to players retreating to Centarious. Although this effect may seem logically backwards (a successful measurement results in an undesirable game outcome), we wanted players to intuit that entangled states are hard to maintain by "fighting" to keep their ships inside Entanglion.

At the beginning of the game, players have a high chance of succeeding in evading planetary defenses as the detection rate starts at a low value: 1 for an easy game, 3 for a harder game. However, when their ships are detected, the detection

rate increases, making subsequent "measurements" harder. This effect models the fragility of quantum states; as of this writing, quantum states can only be maintained for about 90 microseconds [16] before they decohere to the classical state of 0 (also called the ground state).

The short decoherence time also puts a limit on the depth of quantum circuits. Each quantum gate takes some amount of time to be applied, so a circuit that is too deep may require more time to execute than the coherence time of a qubit. We model this idea by using a fixed-length quantum circuit (the "engine control" space where players play engine cards). When that circuit is filled, it triggers a "quantum event." These events add a random, fun element to the game as they may either be beneficial to players (e.g. providing extra navigation options) or harmful (e.g. increasing the detection rate).

Achieving entanglement. In a quantum circuit, entanglement is created using a Hadamard (H) gate to create a superposition in one qubit, and then entangling it with another qubit in a classical state using a Controlled Not (CNOT). This concept is perhaps the most important one we wanted players to learn by playing the game.

Building a real quantum computer. Quantum computers are not just theoretical constructs; IBM, for example, has made 5-qubit and 16-qubit quantum computers publicly available for anyone to program using web interfaces [17] and programming SDKs [18]. The goal of the game is to assemble a quantum computer in order to showcase the kinds of hardware and software components used in building an actual quantum computer. These components include dilution refrigerators, which keep the superconducting materials that implement qubits very, very cold, magnetic shielding, which prevents qubits from decohering due to stray magnetic interference, and quantum error correction, the idea that multiple physical qubits can simulate an error-resilient logical qubit.

Design Process

Our main goal was to develop a game that was not only fun, but also technically accurate. As we ourselves are not experts in quantum computing, we used an iterative design process with feedback from a team of quantum scientists to ensure our designs were technically sound.

The core game went through five major design iterations, which we refer to as $V1$ through $V5$ [1]. We didn't begin our design process with hard requirements about the quantum concepts we wanted to include, but rather we tried to simulate as much of a quantum system as possible on paper and then simplified or dropped concepts that were too difficult to model. In each iteration, we also brainstormed game mechanics that would fit our current model and be fun to play. We made extensive use of paper prototyping as this allowed us to rapidly develop concepts, try them out ourselves, and then get feedback from our quantum scientists when we felt the prototype was ready. Their feedback was incorporated into the next design iteration. We also evaluated later prototypes with other colleagues of ours who were not well-versed in quantum computing to understand whether the game mechanics made sense to them and to gauge their enjoyment. Figure 3 includes pictures of each major iteration of the game, showing how our designs evolved and matured over time.

[1]The final, open-sourced version of Entanglion is $V5$.

Iteration $V1$

The first iteration of our game was a quick prototype to validate whether we *could* simulate some aspects of a quantum system on paper. It introduced players to the concept of programming three qubits using a set of 5 different quantum gates. Players had to use these gates to put the qubits into different predetermined states and would score points accordingly. Our own testing revealed that programming three qubits was too complex, even for our quantum computing experts. We also discovered the mechanics of how one of the gates operated on quantum state were too difficult to model on paper and dropped it from subsequent iterations.

Iterations $V2$ and $V3$

Our main goal for the next iteration was to design an enticing goal for the game – to build a quantum computer from its constituent components – using points obtained by manipulating quantum states. We also wanted to clearly highlight the differences between classical states, superposition states, and entanglement states. Qubits were represented with cubes sitting on a 2x2 matrix showing each of the four different classical states (00, 01, 10, 11), and players earned points by "betting" which state they could put the qubits into from their current configuration. We felt comfortable with the game mechanics when playing amongst ourselves, and created $V3$ as a higher-fidelity prototype of $V2$ in order to enable easier testing with our quantum scientists.

The feedback from our quantum scientists was that the betting mechanics were fun, but they were critical of our technical accuracy. They remarked that the game was "too classical" and "not quantum enough," because our model of representing qubit state as a 2x2 grid was unable to clearly distinguish when qubits were in a classical, superposition, or entanglement state. They sent us back to the drawing board to come up with new ideas that would more accurately represent when qubits were in each of these states.

Iterations $V4$ and $V5$

We made a radical change to the game's design in $V4$ by explicitly representing quantum states as different physical "places" on the game board, with corresponding transitions determined by the quantum gates. This idea came from our observations that the quantum scientists kept trying to compute which classical, superposition, or entanglement state the qubits were in based on which gates they had played. Some did this computation on paper, and others (impressively) in their heads. We felt that this superhuman ability was not what we expected of our players, so we decided to explicitly map out all the quantum states and the transitions between them (by pre-computing the math [2]) on the game board. Once we drew out this map on paper, we instantly thought of using a space metaphor with qubit states represented as planets.

[2]This task was not trivial. It took three quantum scientists multiple attempts to perform the math to map out these states and reduce it to the form used in the game board.



Figure 3. Evolution of Entanglion. Our initial paper prototypes borrowed materials from other board games. Our final *V*5 design is shown in Figure 1.

Another major change in *V*4 was making the game *cooperative* rather than *competitive*. We noticed during many of our playtesting sessions how players would communicate with each other to try and understand how their actions would affect the state of the qubits, and we felt this was an opportunity for the game to actively encourage conversations to facilitate learning by establishing positive interdependence [28]. In order to enable players to work *with* each other, they now needed to work *against* the game. We introduced the "detection rate" as a way to model the buildup of error in a quantum system, and players lost the game when this buildup became too large.

We received much positive feedback on these changes in our playtesting sessions. Our quantum scientists felt our representation accurately modeled quantum states and the transitions between states, and they also started having fun playing, rather than just sampling a little bit of play before asking questions and giving lengthy feedback. The final iteration, *V*5, included a lot of iterative refinements on *V*4 and the creation of production-ready assets.

Calibration of Game Difficulty

Experience of flow in an activity is characterized by an intense, focused concentration on the present moment with intrinsic rewards stemming from one's own agency in the experience [9]. Flow results from receiving immediate feedback from one's actions and feelings that one's actions give them the potential to succeed [8]. Great games are able to challenge players in just the right amount, so that even in difficult situations, players can strategize about their actions to find a (potentially) winning outcome. With Entanglion, even though our primary motivation had been to create an educational artifact, we very much realized that we were also designing a *game* that had to be fun and engaging enough to impart a flow experience. If it was too easy or too hard, we felt that players would not invest the time to reap the educational benefits.

The primary "lever" for determining the difficulty of our game lay in the detection rate scale. Each time players travel to a planet in Entanglion, and each time they attempt to retrieve a quantum component, they must roll the Entanglion die and achieve a result greater than the current detection rate. Once the detection rate reaches the last level on the scale (represented by an *X*), they lose the game. As game designers, we were able to change this scale to make the game easier or harder. One challenge we faced in designing this scale was in having enough people playtest it in order to be confident that the game wasn't too easy or too hard. As much as the game's creators (the first two authors) loved playing the game during development, they felt it best not to completely trust their own intuition (or skill) in calibrating the game's difficulty.

We used what we felt to be a creative approach to calibrate difficulty: we implemented a simulator for Entanglion with AI players to play it. These simulated games helped us understand the extent to which different detection rate scales led to victory or defeat: to test a new variant of the detection rate scale, we changed a little code and then ran a batch of game simulations to understand how often the AI players won or lost. Too much of either was deemed undesirable.

We developed eight variants of the detection rate scale and the AI helped us filter out variants that were too easy. For the rest, we (the first two authors) played with each other to see which ones gave us an optimal flow experience [8]: the feeling that there was a potential to win, even in hard situations, and the feeling of being engrossed in the experience. The scales we liked had corresponding AI win rates of about 50-60%, which also gave us confidence that the difficulty was neither too easy nor too hard. The actual detection rate scale used in the game – $1,2,2,3,3,4,4,5,5,6,7,X$ – was a direct result of the our use of the AI simulation.

Implementation

Our simulator was implemented in Swift in order to leverage the GameplayKit API [19]. This API provides functions for implementing AI "strategists," including one that uses a minimax search strategy to search a game's state space and select optimal moves (GKMinmaxStrategist). We implmented all of Entanglion's rules and game logic in the simulator, including the different actions performable on a turn, the effects of quantum components and quantum events, the transitions between planets in the quantum universe, and the numerous occasions on which a die must be rolled to determine an outcome.

The AI strategist requires several components to be defined in order to be able to make decisions about actions to take in the game. These include a data structure that encapsulates the entire state of the game, a method that examines a game's state and determines the set of possible moves for a given player, and a method that produces a numerical evaluation of a game's state (i.e. a scoring function).

We discuss a few interesting design points of our AI implementation, especially as we found GameplayKit's off-the-shelf implementation of minimax significantly helpful and easily adapted from a competitive to a collaborative situation.

Turn model. The minimax algorithm was developed to select moves in an adversarial context, maximizing a player's gains and minimizing the gains of their opponent. However, as Entanglion is a cooperative game, the "min" aspect of minimax is not applicable. To enable minimax for a collaborative situation, we structured player turns in the manner shown in Figure 4. A player's turn is split into two phases: an optional action performed at the start of the turn (the Qubit Interconnect ability), followed by a second turn phase in which the main game actions may be performed, such as playing or exchanging engine cards, playing quantum event cards, or retrieving quantum components. To avoid the "min" step of minimax, when Player A finishes the first phase of their turn and the AI considers possible moves for Player B, we only allow Player B to pass their turn back to Player A, even though "pass" is not a valid action in the actual game. This "fake turn" makes a full logical turn correspond to a depth of 3 in the state space tree: Player A's first phase, Player B's forced pass, Player A's second phase. In order for the AI to be able to plan far ahead enough to enter Entanglion (by playing H and CNOT), we used a search tree depth of 9, corresponding to a lookahead of 3 full moves. Larger search depths resulted in much longer compute times for the AI without providing much benefit in the quality of the decisions made.

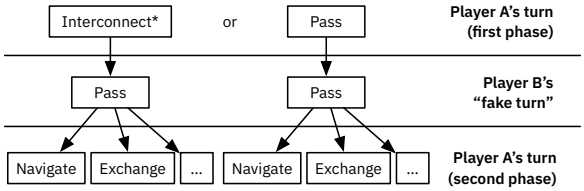


Figure 4. Anatomy of a logical turn. *Exchanging an engine card with the other player may only be done at the beginning of the turn, before any other actions are taken, if the player possesses Qubit Interconnect.

Scoring function. In order for the AI to make progress toward the goal of collecting all eight quantum components, we needed to craft a function that would score a game's state. Our naïve solution was to give a higher score to states in which more quantum components were collected. However, in practice, this led to an AI that behaved somewhat haphazardly as it was unable to effectively plan a strategy for entering Entanglion to obtain the components. We crafted a more nuanced scoring function, shown below. An important lesson we learned in crafting this function was to include terms for all of the intermediate states we wanted to push the AI toward (with positive weights) or away from (with negative weights). The weights $\alpha_0 \ldots \alpha_6$ were determined empirically by examining simulation traces, observing where the AI got stuck, and making appropriate adjustments.

$$S(s) = \alpha_0 \cdot QC + \alpha_1 \cdot CP + \alpha_2 \cdot EC + \alpha_3 \cdot CC + \alpha_4 \cdot CS + \alpha_5 \cdot SS + \alpha_6 \cdot EE$$

where $S(s)$ is the score of game state s, QC is the normalized weight of held quantum components (as some components are more valuable than others, +++), CP is 1 when players are orbiting a planet with a quantum component (++), EC is the number of event cards held by both players (+), CC is 1 when both ships are in Centarious (-), CS is 1 when one ship is in Centarious and the other is in Superious (+), SS is 1 when both ships are in Superious (-), and EE is 1 when both ships are in Entanglion (+).

Optimistic AI. When considering possible moves, the AI sometimes found itself in a state where it had to make a die roll. In early versions of the simulator, we let the AI roll the die to determine what to do, but we sometimes noticed it made sub-optimal decisions, such as not retrieving a quantum component when one was available because it thought it would fail the die roll. We felt human players would never do this, as the only way to win is to retrieve the components. Thus, we made our AI optimistic by having it speculate that any die roll it made would be successful against the current detection rate.

Results

We ran 1,000 simulated AI games with an initial detection rate of 1 (easy). Of these, 939 games finished in less than 500 turns; 61 games were halted at 500 turns as the AI players got stuck and couldn't finish the game. Overall, the AI won 62% of the games and lost 38% of them. The mean detection rate for won games was 3.6 (SD=2.1), corresponding to the 2nd "3" on the detection rate scale. Roughly 8% of games were won at the initial detection rate of 1, leading us to introduce the more difficult variant of playing with an initial detection rate of 3. Interestingly, two games were won with a detection rate of 7 indicating that it is possible, though highly unlikely, to win very close to the end.

In addition to examining the detection rate, we created a simple linear regression model to understand the effect of certain game events and mechanics on winning (adjusted $R^2 = 0.44$). Although most of these results tracked with our own intuition, it was reassuring to see statistical evidence that the mechanics operated in the way we anticipated.

- The "Bit Flip Error" quantum event, which resets the detection rate to "4", turned out to have a net positive effect on winning ($p < .001$).
- The "Spooky Action" quantum event made it harder to win, as it causes players to lose a quantum component they have already collected ($p = .001$).
- The "Wave Function Collapse" quantum event, which reduces the detection rate by 2, increased the likelihood of winning ($p < .001$).
- Evading orbital defenses (obviously) increased the likelihood of winning ($p < .001$).
- Possession of the "Quantum Programming" component, which enables players to bypass orbital defenses when traveling to a planet that does not have a quantum component, did not affect winning ($p = n.s.$). This result was surprising as in our own playtesting, a common strategy was to obtain this component as early as possible to make it easier to navigate Entanglion.

PLAYTESTING

Our overall goal in designing Entanglion was to create an enjoyable and engaging game that exposed players to the basic principles of quantum computing. While our internal playtesting with quantum scientists was useful at ensuring the technical soundness of our game mechanics and the ways in which we represented quantum computing concepts, we also sought to validate the game by having members of two of our target audiences play it: (1) industry professionals, such as graduate students, postdocs, professors, and scientists, who are already engaging with quantum computers, and (2) students, who are growing up in a world that is becoming increasingly quantum ready. Our protocols for playtesting were reviewed and approved by our institution's review board, and all participants received a boxed copy of Entanglion.

Industry professionals (IP). We ran a playtesting session for attendees of a quantum computing conference hosted at our research lab (N=36). Although we do not have specific demographics on this group, the conference was generally attended by students, professors, and industry researchers in the fields of quantum computing, quantum information science, and physics.

Middle and high school students (MHS). We worked with administrators from a local middle/high school to identify classes that would be able to participate in a playtesting session. We selected two classes to playtest with, one of 8th graders (N=29 students, 14-15 years old) and one of 12th graders (N=33 students, 17-18 years old). The age difference between these two classes helped us understand the age-appropriateness of our game. As the participants in this study were minors, we obtained written and verbal assent from each student to participate, and written informed consent from the student's parent or legal guardian. We also received written approval from the school's superintendent to conduct our study.

Methods

We used a mixed-methods approach in our evaluation, collecting a variety of qualitative and quantitative data. Our evaluation with industry professionals focused on their overall qualitative impressions of the game and whether they felt it was valuable as an educational tool. We also asked about which aspects of the game they enjoyed the most and which may have been confusing or difficult. As this was our first public disclosure of the game, and due to time constraints, we were primarily interested in obtaining quick high-level feedback on the overall concept and mechanics, rather than collecting detailed quantitative data.

For our evaluation with students, we focused on quantifying the experience of playing the game using the Game Experience Questionnaire (GEQ) core module [15]. The GEQ measures seven dimensions of a game experience: challenge, competence, flow, positive and negative affect, sensory and imaginative immersion, and tension/annoyance. Participants rate statements such as, "I was good at it" and "I lost track of time" on a 5-point Likert scale ("not at all" to "extremely"). We also asked two open-ended questions to assess what students had learned and to gauge their general interest in quantum computing: "In your own words, define quantum computing" and "What are your thoughts about the future of quantum computing?" We only asked these questions at the end of gameplay as we expected students to have a minimal background in quantum and we wanted to maximize the amount of time playing the game.

In each session, participants were grouped randomly. Industry professionals played in groups of four to six (2-3 people per spaceship) due to the limited availability of game prototypes, and students played in pairs (one person per spaceship). Each session began with an intro to the game, an explanation of the rules, and a walkthrough of a few sample moves, which took about 15-20 minutes. Next, participants were given about 60-75 minutes to play. All groups began with the easy variant (initial detection rate of 1), but groups that finished before time was called were able to play again on a harder variant. At the end, participants were asked to fill out the survey. Figure 5 shows participants from an 8th grade class playing the game.

As participants played the game, our research team observed play and answered questions about game mechanics.

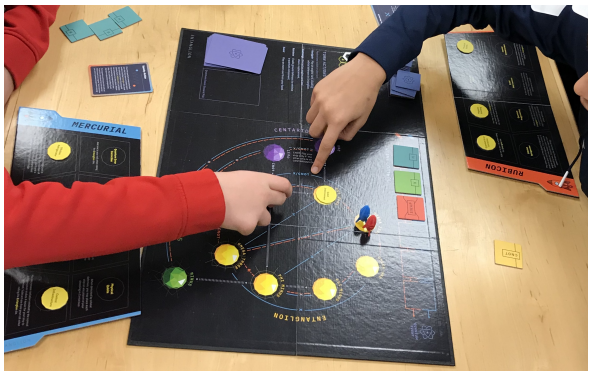


Figure 5. Playtesting *Entanglion* with 8th graders.

PLAYTESTING RESULTS

Industry Professionals

Twenty-two of our industry professional participants (69%) provided written comments after playing the game [3]. We received many comments praising the design of the game, its technical accuracy, and its value in educational settings.

"I enjoyed it very much, and was especially impressed by the careful and elegant design! I think it could be an excellent tool to provide information about how quantum gates act on entangled states." (P1, M, physics doctoral student)

"I was pleasantly surprised at the correspondence between the game board and the physics of a 2-qubit system." (P3, M, quantum scientist)

"Very cool to represent quantum states as planets. Moving between planets with gates a very logical mechanism." (P2, M, physics doctoral student)

We also received conflicting comments on its difficulty; one participant mentioned that they felt "punished" as the detection rate got higher, but another said that the game could be made "more difficult." Another issue discovered by participants is that players could keep passing their turn back and forth by exchanging engine cards, with no penalty or time pressure.

"For an initial game it seemed to have a good difficult[y] as a co-op game. I'm hoping some of the smaller issues such as no time pressure and hand management get addressed. Maybe even have various levels of difficulty?" (P13, M, physics doctoral student)

To address this feedback, we introduced a new engine card called PROBE with a story element that "your ships have been discovered by a probe from the Entanglion system." Upon drawing it, players are forced to perform a planetary defense die roll. This mechanic pushes the game forward by forcing a chance for the detection rate to be increased, dissuading a strategy of continuously exchange engine cards.

[3]As our game session was over lunch, many participants rushed out of the room to attend the next talk.

Participants also had mixed feelings on our use of cooperative mechanics. Some enjoyed the cooperation, and some felt that a competitive game would have been more compelling.

"I feel like most people prefer competitive games over cooperative ones." (P2, M, physics doctoral student)

"The cooperation is fun." (P7, M, quantum computing doctoral student)

"Needs to be more competitive and allow multiplayer." (P5, F, physics doctoral student)

Overall, we received a lot of positive feedback from our participants and they really enjoyed our game.

"It was great. A very playful way to get into a quantum mindset, especially for people like me who have little background in the area." (P18, M, physiologist)

"I think it's awesome! It was obviously very well thought-out." (P15, M, physics doctoral student)

Students

Game Experience

Students also liked Entanglion, giving it generally favorable game experience ratings (Figure 6). Ratings of positive affect (M=3.1, SD=1.0) and sensory & imaginative immersion (M=3.0, SD=1.0) fell in the middle of the scale, and negative affect (M=2.4, SD=0.9) and tension/annoyance (M=2.2, SD=1.0) were rated lower. The difficulty of our game was also balanced, with ratings of challenge (M=2.6, SD=0.7) and competence (M=3.0, SD=1.0) falling at roughly the scale midpoint.

One participant expressed excitement over the prospect of being able to play the game at home, "I'm excited about taking this game home" (F, 8th grade). Another said, "It was complicated at first, but once you get the hang of it, it's fun to play" (M, 12th grade). This feedback demonstrates the positive experience students had playing Entanglion.

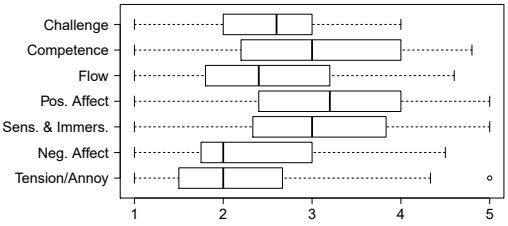


Figure 6. Game Experience Questionnaire scale ratings. Higher numbers indicate higher ratings for each construct.

Impressions of Quantum

We uncovered a number of interesting themes in the responses from students about their understanding of quantum computing and their thoughts about its future, summarized in Table 1. Students' abilities to define quantum computing were varied. Of the 27 12th graders who responded to the question, 4 (15%) understood that it was about computing using quantum mechanical phenomena. Eighth graders' responses were less sophisticated and mentioned that quantum had to do with computation (13%), was related to quantum physics (13%), or was

Theme	Examples	Percentage of students
Unsure how to define quantum	"Not sure what quantum computing is"	21%
Self-referential definition of quantum	"Quantum computing is when you compute quantumly"	14%
Definition of quantum specific to game mechanics	"Collecting pieces from Entanglion", "The study of developing technology which calculates quick routes through hyperspace paths"	12%
Quantum will change the world, has bright future	"I think it will help people in the future", "I think it will change the world"	21%
Quantum is cool, interesting, fun, good, and/or useful	"I think it is cool and exciting", "I think it is cool and really interesting"	37%
No future aspiration to study	"I am not really interesting in that being my future "	12%

Table 1. Emergent themes amongst students when asked to define quantum computing and share their thoughts on its future. Percentages are of the number of students who responded to the question (N=43).

about "computing quantumly" (26%). One 8th grader grasped the complexity of quantum, responding that it was "extremely confusing and complicated," and two 12th graders reported that quantum computing was "computing for smart people." Regarding their views on the future of quantum computing, a little more than a third of students felt quantum computing was cool, interesting, fun, or good (37%). About 21% felt that quantum computing would change the world and had a bright future, although 12% of students commented that they would not be interested in pursuing a career in it.

DISCUSSION

We reflect upon several themes that emerged from our design process and observations of gameplay.

Competition vs. Collaboration

We were motivated to create a collaborative game because collaborative gaming encourages social interactions and creates an intragroup dependency that encourages learning and sharing of information during the game-playing process [24]. However, a number of IP and MHS participants were surprised to find that our game was collaborative rather than competitive. Some even expressed dismay upon the discovery. One student said, upon discovering that the goal of the game was to work *with* your partner to win, "Then what is the point if we are not competing?" (M, 8th grade). However, in all cases after players began playing together, we observed much conversation about the formulation of a winning strategy. We speculated that a cooperative game would force players to ask each other questions like, "how can we reach this planet?" and "where does that gate take us?" and in many cases, these were exactly the questions that participants asked of each other.

Confusing Mechanics

Some IP and MHS participants expressed confusion over how to get their spaceships to enter Entanglion. We attempted to design the game board to make it visually clear how this is accomplished (gray barred lines indicating one ship moves from Superious and the other from Centarious), but we received many questions asking if they were "doing it right." We are not entirely dissuaded by this confusion, as this mechanic is perhaps the single most important lesson we aim to teach: entangled states are created by conditioning the value of a qubit on one that is in superposition (i.e., H + CNOT = entanglement). In an educational setting, we recommend spending more time to explain this mechanic than we allocated in our studies. We also expect players to internalize this rule after repeated play sessions.

Related to entering Entanglion is the notion that ships always move *together* when in Entanglion. Some IP and MHS participants also struggled to learn this concept, demonstrated by attempts to move their spaceships independently inside Entanglion. We do not wish to label such behavior as playing the game *incorrectly* [4], but rather, we hope that the process of learning and internalizing the rule that "spaceships always travel together in Entanglion" leads to an understanding that two entangled qubits always share the same state.

Another mechanic that was overlooked by players, especially on their first game, was the effect of the quantum components. These components make permanent alterations to gameplay, such as enabling a player to re-roll a die when the result is unfavorable. For new players, these rules would sometimes go overlooked as much of their attention and focus was on learning the basic mechanics of the game *first*, before they were able to begin thinking about how those basic mechanics might *change* as the game unfolded. We do not necessarily see this play style as wrong, either. Navigating the galaxies of Entanglion takes a lot of focus for new players, and a broader design lesson would be to use simpler mechanics for the first few games and then layer in more complex mechanics as players become more skilled. We have seen a similar strategy used in other commercial board games as well, such as Alchemists [21], which defines simpler mechanics for new players and more advanced mechanics for experienced players.

Use of AI to Calibrate Difficulty

Our use of AI significantly helped us in calibrating game difficulty. With the AI simulation, we were able to quantitatively compare many more versions of the detection rate scale than we could have by playing on our own. Although we do not claim the AI perfectly models how people play, our MHS participants rated the challenge of the game in the middle of the scale: not too easy and not too difficult. We see AI simulation as a promising means to calibrate difficulty of board games and we would recommend this approach for the design of other educational games as well. Although implementing a simulator for a game's mechanics may be a complex task, if a game designer does undertake the effort, they can leverage it to create a digital version of their game.

[4]Presumably, the game can be played in this fashion, although it might be somewhat less challenging.

Impressions of Quantum

We were delighted to see that a little more than a third of students had a positive impression of quantum computing after playing our game, by commenting that it was "cool," "fun," "interesting," and "useful," even though many were unable to provide a clear definition of what quantum computing exactly was. Contrarily, our game may have dissuaded some students because they felt only "smart people" could grasp it. We readily admit that quantum computing is not for everyone, but we are encouraged by the positive impressions made.

Game Experience

We set out to create a highly-enjoyable game, although our GEQ scores, while generally encouraging, were not at the very high ends of the scale. We believe one of the reasons for this is due to the limited amount of time students had to engage with the game (about 75 minutes), and the learning curve needed to play the game independently. In addition, after playing countless games of Entanglion ourselves, we feel that replayability may be limited and deeper strategic mechanics would make the game more engaging and immersive. We are hopeful that expansions to the Entanglion universe will be created to address this issue, as it is an open source game that anyone can extend, and we invite the community to create such expansions.

Game-Based Learning For Highly Technical Domains

One of our biggest challenges during the design of our game was striking a balance between technical accuracy and our educational objectives with enjoyable game mechanics. This balance is important because a game has to be compelling and enjoyable enough to play leisurely, regardless of the educational content. Although we did not find these two goals to be mutually exclusive in the design of our game, we did find that time spent refining the game mechanics took time away from ensuring technical accuracy, and vica versa. For example, in early iterations of the game, we developed mechanics that were quite enjoyable but technically inaccurate, leading us back to the drawing board. We reflect on two areas in which designers of educational games for highly technical subjects should focus their attention.

Defining learning objectives. In designing a game to teach a highly technical subject, designers must identify whether the objective of the game is to *introduce* players to concepts in a particular field or to teach individuals how to *master* the technical aspects of the subject. In our game, we placed our emphasis on conceptual learning (familiarizing players with high-level concepts) rather than technical mastery; after playing Entanglion, we hope players would take the next step in learning to programming their own quantum circuits, but the game itself does not explicitly teach this skill. We considered the possibility of tying the game in with an actual quantum simulator in our early ideation sessions, but our desire to focus on conceptual learning led us away from this design.

Reinforcing learning via multiple representations. To help players internalize quantum concepts, our game includes mechanics that map onto real-world quantum mechanical behaviors. For example, we require spaceships to travel together in Entanglion because entangled qubits always share the same state, and the process of encountering planetary defenses mimics the process of measuring a quantum system. However, our playtesting revealed that players did not always pick up on *what* these rules were, nor *why* they were this way. For some mechanics, such as spaceships traveling together, the only indication that this is required was from our own verbal instruction and a description in the rule book. While we might expect new players to diligently read the rules before playing, we realize many won't. Thus, we recommend that important game rules and mechanics be represented in multiple ways across the game materials. Additional iconography or language on the game board could be used to depict how spaceships travel together in Entanglion in addition to the rulebook description. Or, an additional turn phase to check if the ships are in a valid state could be added, with a penalty if they aren't.

LIMITATIONS

We learned many valuable lessons from designing and playtesting our game. Despite the positive feedback we received, there are several limitations we must acknowledge.

Learning Quantum

Our method for evaluating learning effects with students was limited and many of the responses we received were either vague, missing, or inaccurate. We see this work as more of a case study for design, with a formal evaluation of learning outcomes remaining as future work. We anticipate such an evaluation being longitudinal as not many of our IP or MHS playtesters showed a strong mastery of the game concepts after just one session. In addition, this evaluation could examine how easily players are able to program actual quantum circuits after having mastered the game.

Student Non-engagement

Almost a third of students returned blank survey forms (N=19). In addition, some students did not engage with the game during the play session, but rather used the out-of-class time to chat with their friends or conduct other activities unrelated to our game. We believe the reason for this behavior was that the students' regular teacher was absent during our playtesting sessions and a substitute teacher was present instead. The school's supervisor apologized for these students' behaviors and explained that they were less well-behaved with the substitute. In future studies with students, we would reschedule in order to ensure the presence of the regular teacher to maintain discipline and focus on the activity at hand.

CONCLUSION

We presented Entanglion, an open-source board game designed to introduce players to fundamental concepts of quantum computing. Our development process involved many iterations with quantum scientists to develop a technically accurate game for a highly complex field, and a combination of human and AI-based playtesting to tweak the mechanics and calibrate the game's difficulty. Through our playtesting with students and industry professionals, we have shown the game to be fun and engaging while giving a positive impression of quantum computing to its audience.

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