Qupcakery: A Puzzle Game that Introduces Quantum Gates to Young Learners

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ABSTRACT

Quantum computing (QC) is an emerging field at the intersection of computer science and physics. Harnessing the power of quantum mechanics, QC is expected to solve otherwise intractable problems significantly faster, including in encryption, drug development, and optimization. High-quality and accessible QC resources are needed to help students develop the critical skills and confidence to contribute to the field. However, existing programs are often aimed at college students with an advanced mathematics or physics background, shutting out potential innovators.

To make quantum learning resources for a broad, young audience, we designed Qupcakery, a puzzle game that introduces players to several core QC concepts: quantum gates, superposition, and measurement. We present preliminary testing results with both middle school and high school students. Using in-game data, observation notes, and focus group interviews, we identify student challenges and report student feedback. Overall, the game is at an appropriate level for high school students but middle school students need more levels to practice when new concepts are introduced.

CCS CONCEPTS

• **Social and professional topics → K-12 education**; **Informal education**.

KEYWORDS

quantum computing education, game-based learning, quantum gates, K-12 education, informal learning

ACM Reference Format:

Tianle Liu, David Gonzalez-Maldonado, Danielle B. Harlow, Emily E Edwards, and Diana Franklin. 2023. Qupcakery: A Puzzle Game that Introduces Quantum Gates to Young Learners. In *Proceedings of the 54th ACM Technical Symposium on Computer Science Education V. 1 (SIGCSE 2023), March 15–18, 2023, Toronto, ON, Canada.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3545945.3569837

SIGCSE '23, March 15–18, 2023, Toronto, ON, Canada.

ACM ISBN 978-1-4503-9431-4/23/03…$15.00
https://doi.org/10.1145/3545945.3569837

1 INTRODUCTION

Quantum computing (QC) is a rapidly-growing field between computer science and quantum physics. Unlike classical computers, quantum computers utilize quantum mechanics and are fundamentally different at the hardware level. Although not a substitute for classical computers, quantum computers may solve specific tasks much faster than classical computers (e.g. RSA encryption [7]), including intractable problems with significant social impacts (e.g. simulations used for drug design [4]). There is a need for a diverse workforce to both contribute technically [3] and have a voice in the uses of this transformative technology.

Quantum computing exploits superposition, entanglement, and non-determinism, all absent in classical instruction. It is important to expose students to these counter-intuitive concepts at an early age so that students build familiarity and confidence, increasing the chance they would pursue this field, but exposure is limited due to a lack of accessible educational resources. In the US, quantum computing education is mostly targeted at advanced undergraduate or graduate students with an existing technical background in mathematics or physics, posing a high entry barrier. Although there have been some outreach efforts trying to engage K-12 students in quantum computing learning, most of the programs have been ad hoc and not scalable [1, 17].

To fill this gap, we created Qupcakery, a food-serving style digital puzzle game designed for middle-school (11-14 y.o.) students. The game introduces quantum gates, superposition, measurement, and related quantum computing concepts in a fun way.

In this paper, we present the design of the game and report results from two play testing sessions with middle school (11-13 y.o.) and high school (16-17 y.o.) students. The goal of our study is to evaluate the difficulty of the levels, gauge student engagement, and seek student feedback to inform future development.

2 BACKGROUND

2.1 Game-based Learning

Grounded in motivation theory, well-designed game-based learning experiences are promising for improving learning outcomes [8, 18]. Games are especially appropriate in the quantum context because they provide learners with concrete "objects-to-think-with" [13] that help visualize and solidify elusive quantum concepts.

2.2 K-12 QC Education

Early exposure to advanced STEM topics is critical to promoting student interest and guiding student career choices [11, 12]. Existing efforts in introducing QC into K-12 include a one-week high school module centering on quantum mechanics [14], an individual class module on quantum teleportation [17], games [19], hands-on activities [6], and summer outreach programs [1, 5, 16].

Though not specifically designed for our target population, games have been created for quantum computing learning. The Entanglion board game focuses on state transitions and exposes players to quantum computing properties through game cards[19]; Hello Quantum is a mobile puzzle game where players use quantum gates on a chess board for pattern matching [9]; other games such as Quantum Flytrap's optical-based puzzle games [10] and Quantum Moves 2 [15] expose players to more fundamental physics concepts such as potential wells and wave properties. Although some games report player enjoyment, there hasn't been any research published that digs into specific conceptual challenges.

2.3 Quantum Computing Concepts

Qupcakery involves several QC concepts, including qubit state, qubit gates, superposition, and measurement.

Quantum computers use *quantum bits (qubits)* to store information. Unlike a classical bit which always has a deterministic value of 0 or 1, a qubit can be in a nondeterministic (*superposition*) state.

A qubit in *superposition* exists as a linear combination of 0 and 1, associated with a probabilistic distribution. It is often expressed in *Bra-Ket* notation: $\alpha|0\rangle + \beta|1\rangle$, where $\alpha^2 + \beta^2 = 1$. Such information can be used for calculation but is not directly observable. To obtain a numerical readout, the qubit needs to be *measured*; its output will follow the probabilistic distribution, with $|\alpha|^2$ probability of measuring 0 and $|\beta|^2$ probability of measuring 1.

Classical computers use logic gates to perform bit calculations; similarly, quantum computers also use *quantum logic gates* to perform qubit calculations, which result in quantum states not possible with classical operations. The Hadamard gate, for example, transforms a qubit in the $|0\rangle$ state to the superposition state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.

3 GAME DESIGN

Our design goal is to help players become familiar with quantum gate logic and acquire quantum vocabulary through repeated practice within a convincing game context.

Game Premise Qupcakery is a short-order chef game. An absent-minded cupcake chef owns cupcakery that uses conveyor belts to serve the cupcakes. He makes cupcakes of two flavors — vanilla (0) and chocolate (1). However, he is so busy baking cupcakes that he often serves the wrong flavor of cupcake to his customers. The player uses quantum bakery devices to transform the cupcake to the desired flavor.

Representations Cupcake boxes (Table 1) and quantum baking devices (Table 2) represent qubits and quantum gates, respectively. These concrete, familiar everyday objects, serve as a scaffold for the abstract math concepts. This also helps them visualize, describe, and relate to the embedded quantum concepts.

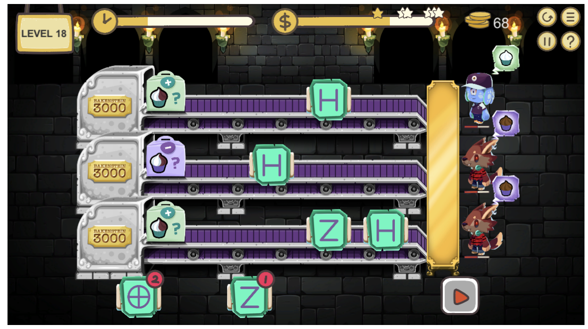


Figure 1: A scene of a puzzle in-game

Cupcake boxes represent the unobserved qubit states, and the act of opening the box represents measurement. Measurement both changes the state to a specific flavor and reveals that end result (flavor). While a cupcake box with a vanilla cupcake on it tells us that the qubit is in state $|0\rangle$ and will output 0 when opened, surprise boxes are in a superposition state, so it displays both flavors and has an equal chance of showing either flavor when opened.

The quantum baking devices behave the same as the actual quantum operations they represent. We gave the gates game-relevant names that are suggestive of what they do. For example, the NOT gate (*Flavor Inverter*) flips the flavor from chocolate to vanilla and vice-versa. The CNOT gate (*Chocolate-Powered Flavor-Inverter*) only applies the NOT gate to the target cupcake if the control cupcake is chocolate ($|0\rangle$), just as in a real CNOT gate. Table 2 provides illustrative examples of how the gates modify (or do not modify) specific cupcake states.

Game Mechanics In the game, players need to solve pattern-matching puzzles. Customers (non-players) arrive from the right of the screen to order the cupcake they want, and pre-baked cupcakes show up at the leftmost end of the conveyor belt. The player can select from the available gates to drag onto the conveyor belts to use them. Once the player thinks they have made the correct arrangement of the gates, they can press the play button at the lower right corner to send the cupcake boxes through the gates and deliver the cupcakes to the customers. Figure 1 shows one puzzle.

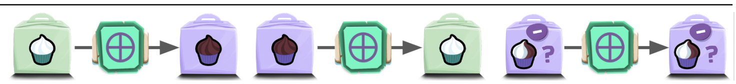
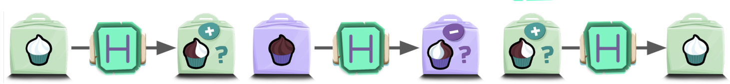
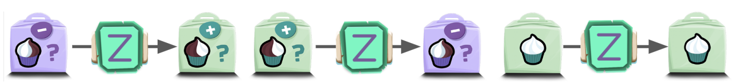
Level Design The levels are designed to progress in complexity by increasing the number of conveyor belts, and introducing new gates and concepts gradually. The game introduces 5 quantum gates in the following levels: NOT:1, SWAP:3; CNOT:8; H:11; Z:13. Whenever a new gate is introduced, players get 1 or 2 easier levels to become familiar with the newly introduced gate, then a harder level that combines puzzles with the new gate and previously-learned gates. During pilot testing, participants played 20 of the 25 available levels, so we focus on those levels in the following sections.

Each level contains 4 - 7 puzzles and lasts from 40 secs to 2 mins. The number of puzzles is chosen such that players can practice with all combinations of newly introduced gate logic with some repetitions. In order to encourage mastery and increase the challenge, we set time limits on each puzzle and level. Once the time has passed, students lose out on coins as the customers leave. Passing each level requires a combination of accuracy and speed, instead of 100% accuracy.

Table 1: Representations of quantum state

Name	In-Game	Mathematical	Description
Vanilla Cupcake		0	Cupcakes represent the obtained numerical values after measuring a qubit. In the game, the cupcakes are revealed after the customers receive and open the cupcake boxes.
Chocolate Cupcake		1	
Vanilla Cupcake Box		$\|0\rangle$	Regular cupcake boxes represent qubits in deterministic states. A vanilla cupcake box will always output a vanilla cupcake and a chocolate cupcake box will always output a chocolate cupcake.
Chocolate Cupcake Box		$\|1\rangle$	
Positive Surprise Box		$\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$	Surprise boxes represent superposition states that have an equal possibility of being measured to chocolate or vanilla. If a customer orders for a surprise, they will be happy getting either of these boxes.
Negative Surprise Box		$\frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)$	

Table 2: Representations of quantum operations

Name	Description	Examples - input -> gate -> output
Flavor-Inverter (NOT Gate)	Toggles between chocolate and vanilla. No operation on surprise boxes.	
Flavor-Swapper (SWAP Gate)	Trades the values of two cupcakes.	
Chocolate-Powered Flavor-Inverter (Controlled-NOT Gate)	Conditional gate that applies a NOT to the target (cross) only if the control (dot) is chocolate, otherwise no operation.	
Surprise Wrapper (H Gate)	Converts regular cupcake boxes to surprise boxes of the matching color and back again.	
Surprise-Inverter (Z Gate)	Toggles surprise boxes between positive and negative. No operation on regular boxes.	

Game feedback Players receive feedback on their solutions through a system of customer reactions and stars. This will reward players when they are doing well, boosting their confidence, which will likely improve their learning and performance, as suggested by self-efficacy theory [2]. Once the customers receive the cupcake boxes, they open them to reveal the cupcakes inside. If the cupcake matches their order, the customer will be happy and leave money for the player; if it does not, the customer will be sad and leave without paying. Students earn stars based on money earned at the level. The reward system is paired with a timing system to make the game challenging. Each set of customers has a set patience limit, and once that runs out, the customers will leave without paying.

4 METHODS

4.1 Research Context

This IRB-approved study uses quantitative and qualitative data collected from two pilot testing sessions conducted on the campus of a research university in the Midwestern United States.

Middle School 14 students aged 10-12 enrolled in a two-week STEM summer camp. The game session was divided into two 20-minute intervals, each preceded by a short 5-minute presentation - the first presentation was on game mechanics and the second was on mystery boxes and superposition. Students were asked to only play levels 1-10 in the first interval and levels 11-20 after the second presentation (mystery boxes were introduced in level 11).

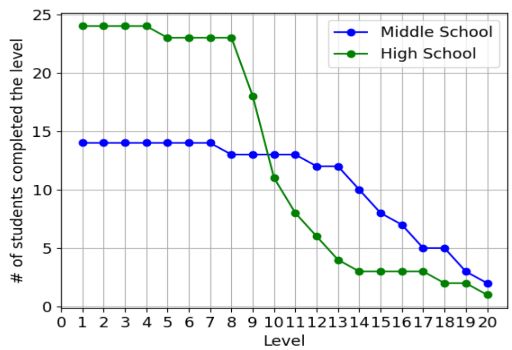


Figure 2: Number of students completed each level

Students then participated in a 15-minute focus group interview of 2-4 students.

High School The second testing session was conducted with 32 rising juniors (16-17 y.o.) participating in a college readiness program. After a brief introduction to the game premise, the students first played Qupcakery for about 15-20 minutes and then a different QIS-inspired game (not the subject of this paper) for another 15 minutes. After playing both of the games, students participated in a 15-minute focus group interview of 4-6 students. We analyzed in-game data from the 24 students who arrived on time and focus group data from all 32 students.

4.2 Data Collection

Quantitative data of in-game data: puzzle attempts, solution correctness, level result (win/loss/quit), and stars earned for every attempted level.

Qualitative data included observation field notes of student behaviors, struggles, and questions during gameplay and answers to focus group questions (rate how fun they thought the game was, what they liked about the game, what they found challenging, what they thought the different gates do, and how they thought the game related to quantum computing).

5 RESULTS

We present data on students' game performance, including what levels they were able to complete successfully and how well they performed at each level.

5.1 Overall Completion

We first wanted to understand how challenging the game was for players. We use two pieces of information: how many players attempted each level and their success at those attempts.

Figure 2 shows the number of students that successfully completed each level (gaining at least one star). Note that students could only attempt a level after passing the previous one.

We can see that the middle school students completed many levels, with almost all students completing at least 13 levels. High school students, on the other hand, only completed 8 levels before experiencing a sharp drop-off. Further inspection of level performance can answer whether the drop-off was due to the level of challenge or the short play duration.

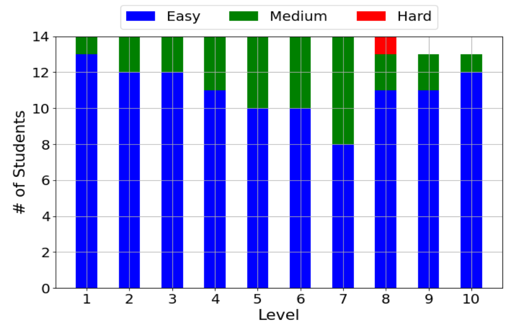


Figure 3: Middle school level performance

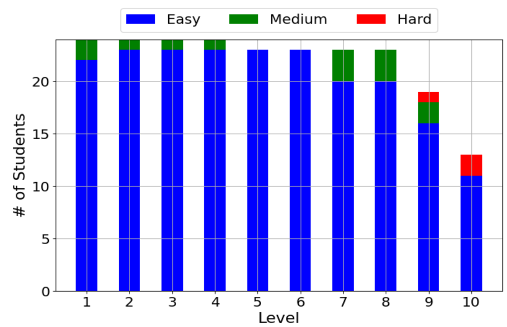


Figure 4: High school level performance

Figures 3 and 4 show how difficult each level was for students to pass. Level difficulty is measured through student performance, categorized as follows:

- Easy: Passed on their first attempt.
- Medium: Failed on the first attempt but passed on a later attempt.
- Hard: Never passed.

Due to space constraints, we show the first 10 levels. The rest of the data shows similar trends.

We can see that through level 9, most high school students completed levels on the first attempt. This implies that the observed drop in completion rate was due to time constraints, not difficulty. The middle school students, on the other hand, were much more challenged by the levels. In level 7, for example, almost half of the students required multiple attempts.

Field notes reveal that many middle school students sought 1-on-1 support to clarify how a gate works or get help solving a specific puzzle, whereas high school students played largely independently. Part of the challenge for middle school students was that they largely skipped in-game tutorials introducing how each gate works.

5.2 Puzzle Performance

Next, we analyze student performance on each puzzle within the level to identify specific concepts that were especially challenging to students. Note that students can still pass a level if not all puzzles were solved correctly, and students may not attempt every puzzle in each level if they reach the level's time limit before seeing every puzzle. As such, analyzing by puzzle provides a more fine-grain view of student performance.

For each puzzle, we classify each student's performance with a similar classification as the one for level difficulty:

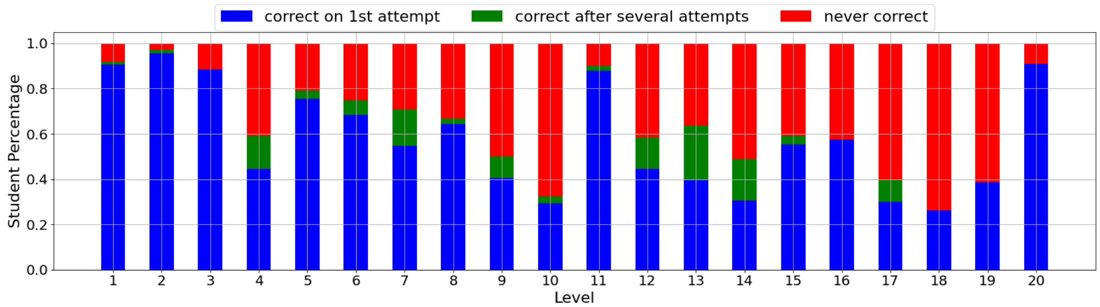


Figure 5: Middle school average puzzle performance per level

- correct solution on the first attempt,
- incorrect solution on the first attempt, but eventually correct,
- never correct.

We then group together the data of all the puzzles for each level and calculate the percentage for each group of students. Figure 5 shows the results for middle school students.

Using this data, we identify concepts present in puzzles that students found particularly easy or particularly difficult.

Level 1-2: NOT gate. All students successfully completed these 2 levels and more than 90% of the time the students correctly solved the puzzle upon the first attempt. This indicates that the NOT gate is conceptually easy for the students to understand.

Level 3-7: SWAP gate. Although all students successfully completed these levels, the drop in average puzzle success rate in level 4 suggests student challenges with the SWAP gate (while the SWAP gate is introduced in level 3, its use is not required until level 4.). Inspecting both focus group notes and in-game recordings of students' attempted solutions, we found that many students misinterpreted the SWAP gate to be a double-NOT gate, applying NOT to two cupcakes rather than swapping their values.

Level 8-10: CNOT gate The relatively low performance across these levels suggests that understanding CNOT was particularly hard for the students. Inspection of the failed attempts showed that some students did not realize the NOT gate on the target is only applied if the source is a chocolate cupcake, while others did not understand that flipping the gate changed its effect.

These misconceptions were further confirmed by the focus group interviews. When asked to explain how CNOT works, many students' responses were similar to the following: *"the top is the same and the bottom one changes. The bottom one changes when it goes through the gate."* Furthermore, levels 9 and 10 required the students to use SWAP gates and CNOT gates together correctly. Since many students had a poor understanding of the SWAP gate, this likely compounded into much lower success rates. Both middle school and high school students struggled with these levels.

Level 11-20: H and Z gate. Completion rates gradually dropped after level 11, implying an increase in level difficulty, students losing focus after playing so long, or students running out of time. Based on observation notes, several students did not understand why they did not get any money if they gave a mystery box to a customer ordering a regular box or vice versa. A few high school students completed these levels despite the short play session. Field notes indicate that these students were especially quick in their completion of the puzzles in all game levels.

5.3 Student feedback

Most students enjoyed the game, but a few middle school students felt the game was too difficult. In the focus groups, we asked the students to rate how fun they found the game was on a scale of 1-10 (Figure 6). Most students thought the game was quite fun, giving an average rating of 7. A few middle school students didn't enjoy the game because they felt the game became too difficult too quickly, and the puzzles timed out too quickly.

The game design was a major attraction for middle school students. When asked what they liked most about the game, middle school students mainly talked about the game arts and the game mechanics:

> *S1: "It was cool to change the cupcake into a mystery."*
> *S2: "I like that you can switch it and change it. (I like) the design."*
> *S3: "(I) love cupcakes, the characters are adorable. And I love the name Qupcakery."*

High school students liked that the game was challenging enough to be interesting but not overwhelming. Many students felt the game was well-paced and did a good job by teaching them through doing:

> *S1: "For the complicated switches it was fun to figure them out, and use multiple of them. "*
> *S2: "It had my blood rushing. It was timed so you would want to beat the time. The challenge was what made it interesting."*
> *S3: "It was step by step. Instead of just a bunch of information dumped on you."*
> *S4: "Once played several levels, it became second nature how the gates work. At the beginning I didn't really know how to play the game. I didn't really understand it, but if you just play some random ones. You start to get it a little bit, like the patterns."*

The game also sparked high school students' interest in learning more about quantum computing:

> *S1: "I was curious how it actually aligns with quantum stuff. This game is all about finding patterns. I'm curious to understand what the H and the Z mean."*

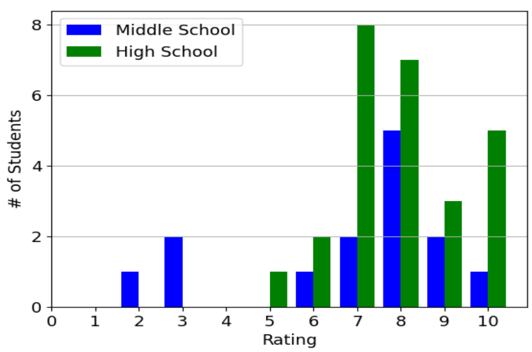


Figure 6: Student ratings of how fun Qupcakery was

S2: "(I) want to understand how superposition is related to the mystery box. Why it's like that? Like the probability where is that coming from?"
S3: "What it means to have a mystery box but still retain its color?"

6 DISCUSSION

In this section, we discuss three aspects of design that our data revealed: adjusting the technical difficulty of the game levels, choosing analogies that provide the intuition we want about superposition and measurement, and balancing the goals of technical accuracy vs. piquing player interest to learn more about QC.

6.1 Level Difficulty

Although high school students had a shorter play session, they played more independently, were more successful at solving puzzles, and rated the game higher than middle-school students. These findings led us to the conclusion that the game is at an appropriate level for high school students, but the difficulty needs to be adjusted for middle school students - they failed more times, asked more questions, and skipped past the introduction of new gates (whenever a new gate is introduced in the game, a tutorial panel with the gate name, a description of how it works, and pictorial examples (as in Table 2) will pop up for the students to read.

We propose to depend less on the text explanation of how the gate works and more on practice within gameplay. After the short tutorial, the first level that introduces a gate will have more time per puzzle, restrict players to only that one gate, and go through all different combinations of starting states to apply that gate or leave a conveyor belt blank. This will demonstrate the same material as in the tutorial, and they would likely need to repeat the level if they do not understand it yet.

6.2 Quantum Phenomenon meets Games

One major challenge we faced was in applying the quantum phenomenon superposition and measurement to a fun, convincing game world context. Superposition is unobservable in real life, so all relatable analogies are by definition inaccurate, even the simplified version of Schroedinger's Cat analogy (is the cat in the box, with a poison pill that may or may not have gone off, dead or alive?). The cat is either dead or alive, and opening the box provides us the *information* about its state rather than it being in superposition and the measurement changing it to either dead or alive. For us, a box hides the cupcake, and the decor indicates the state. Opening the box measures the value, collapsing it into a simple chocolate or vanilla cupcake. However, this distinction may not be obvious.

Is a customer ordering the *state* it wants or the *measured result* it wants? If a customer asks for a surprise cake that is nondeterministic, they clearly will accept either vanilla or chocolate, so why should they care if they get a deterministic one? If we put a vanilla cupcake in a superposition box, wouldn't they get the same experience of not knowing what it is until they looked at it? Students were confused - they only cared about the measurement outcome, not the state. In the future, we may need to create two versions of the game and test both the playability and the reasonability with students and also the conceptions those choices make in players' minds about superposition and measurement.

6.3 Balancing Interest and Accuracy

Our goal is not to teach QC, but to introduce interesting quantum phenomena, build skills in creating quantum circuits, build confidence in those skills, and spark interest to learn more about QC. While this was just a short play trial focused mostly on gameplay, we did find that the oddities of the surprise boxes and the seemingly random symbols such as H and Z sparked students' curiosity in figuring out why the game was designed in this fashion. This suggests that our game is a great entry point for motivating student interest in learning about QC. In the future, we plan to add more instructional in-game materials in the form of reward stickers, optional short videos, and optional quizzes to help students better make connections to quantum, as well as teacher resources that they can use to use the game within a more formal lesson.

7 CONCLUSIONS

In this paper, we presented the design and the pilot testing results for Qupcakery, a puzzle game for introducing quantum gates and core quantum computing concepts to young learners. We found that the premise and overall game design were engaging for most students, many students successfully used quantum gates to solve puzzles in a short time, and the game piqued student interest.

Gameplay analysis revealed that the game is at an appropriate difficulty for high school students, but more scaffolding is necessary for middle school students, our main target audience. To this end, we identified common student struggles by triangulating between observations, level attempts, focus group notes, and knowledge of level details, and proposed level modifications to scaffold the game better for struggling students.

In our next prototype, we will introduce learning content into the game and conduct further research on student learning outcomes. We hope to find that middle school students find the game well-paced and that some players are able to make connections between the game and fundamental quantum concepts without external intervention.

8 ACKOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant No. 2115780 and 2115843.

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