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DESIGN CHALLENGES FOR SCIENCE GAMES: THE CASE OF A QUANTUM MECHANICS GAME

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The abstract nature of quantum mechanics makes it difficult to visualize. This is one of the reasons it is taught in the language of mathematics. Without an opportunity to directly observe or interact with quantum phenomena, students struggle to develop conceptual understandings of its theories and formulas. In this paper we present the process of designing a digital game that supplements introductory quantum mechanics curricula. We present our design process anchored on three key challenges: 1) drawing upon students' past experiences and knowledge of classical mechanics while at the same time helping them break free of it to understand the unique qualities and characteristics of quantum mechanics; 2) creating an environment that is accurate in its depiction of the mathematical formulations of quantum mechanics while also playful and engaging for students; and 3) developing characters that are relatable to players but also do not reinforce gender stereotypes. Our design process can serve as a useful resource for educational game designers by providing a model for addressing these challenges.

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INTRODUCTION

The quest to uncover the underlying constituents of the world began centuries ago. Democritus (460BC– 370BC) hypothesized that all matter is made of indivisible particles, or "atomos" (Berryman, 2010). Since then, many different atomic models have been developed. Some of the major models include: J. J. Thomson's 'plum pudding model' where electrons rest on a bed of a positively charged atom ("Thomson atomic model", 1999), and Niels Bohr's popular 'Planetary model' of the atom where electrons orbit the nucleus at fixed distances ("Bohr Model," 2008). The most radical (and the most recent) model of the atom is arguably the quantum mechanical model put forward by Erwin Schrödinger, who devised a mathematical equation to explain the wave-particle duality of the electron and how its position is governed by probabilities ("Schrodinger Equation," 1999). In this model, if an electron is confined in a very small 'box' (e.g., an atom or any quantum well), it exhibits strong wave-like characteristics. In its wave-like state, the electron

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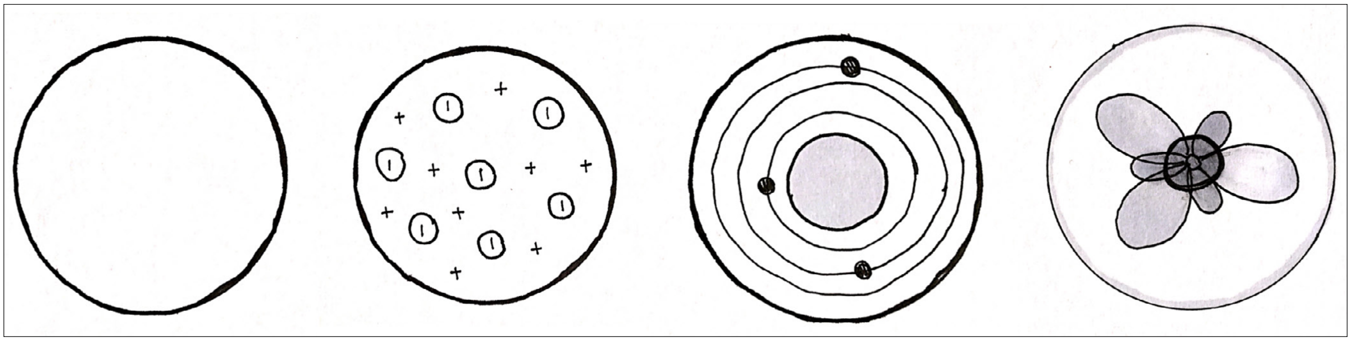

FIGURE 1. Major models of an atom include Democritus', Thomson's, Bohr's, and Schrodinger's model of an atom. (Left to Right) Image Credits: Ridhima Gupta

exists in multiple positions simultaneously. This state can be broken whenever a measurement is made that attempts to locate the electron. Such a measurement temporarily forces the electron into one position. However, this measured position can never be predicted. We can only calculate the probability (or chance) of finding the electron at a given position. The shape of the electron wave (or wave function) determines this probability. This relationship is called the position probability distribution.

Probability is at the heart of most quantum systems which makes them difficult to visualize (Bao & Redish, 2002; Sadaghiani & Bao, 2006). Textbooks and courses focus primarily on the mathematical formulations of quantum mechanics and do not adequately facilitate a conceptual understanding. Consequently, students struggle to visualize quantum phenomena (Mashhadi, 1995; Singh, 2001). This is further compounded by students' lack of direct experience with quantum phenomena, thus making quantum mechanics a challenging subject to teach and learn (Bao & Redish, 2006; Forbus, 1997; Johnston, Crawford, & Fletcher, 1998; Mashhadi, 1995; Singh, 2001; Sadaghiani & Bao, 2006; Vaidyanathan, 2011). Quantum mechanics is the foundation of many fields such as material sciences, physics, and electrical engineering and constitutes the core of many undergraduate curricula, making it crucial and worthwhile to develop tools to help students better understand it.

The project described in this paper began in 2014 as an interdisciplinary effort by designers, developers, and engineers. The result of that effort is a 2-D platformer computer game titled *Particle in a Box* that visualizes the concepts of quantum mechanics as part of an experiential environment. The title of the game refers to the '*Particle in a Box*' system in quantum mechanics. This system is frequently used in courses and textbooks to familiarize students with basic quantum phenomena as it lends itself to conceptual analysis and incorporates all the foundational concepts. The game aims to supplement the learning of introductory quantum concepts such as measurement, probability, energy levels, and the potential profile for undergraduate students.

This paper presents the process and rationale for our design decisions behind *Particle in a Box*. Previous research on educational games (Connolly, Boyle, Macarthur, Hainey, & Boyle, 2012; Clark, Tanner-Smith, & Killingsworth, 2016; Clark et al., 2011; Squire, Barnett, Grant, & Higginbotham, 2004) has primarily focused on evaluating their effectiveness, yet the design process and rationale have been frequently overlooked. Prior research that focused on design has often aimed to produce broad guidelines for educational games (e.g., Dondlinger, 2007; Gee, 2005; Marne et al., 2012; Moreno-Ger, Burgos, Martínez-Ortiz, Sierra, & Fernández-Manjón, 2008). These guidelines, however, tend to be too general and do not address the intricacies of design decisions that shape the characteristic qualities of such environments. This is in part due to the difficulty of writing and publishing design processes without generalizing (Boling, 2010; Smith, 2010). Nonetheless, a detailed description of the rationale for the game environment and its key characteristics contain a wealth of design knowledge. It is in this spirit that we outline the design thinking in the background of designing *Particle in a Box* –to inform educational game designers as they design their own digital educational environments, even if the content of their game is unrelated to quantum mechanics. We anchor our design description around three overarching challenges in educational game design in a way that others can learn from our general approach, successes, and failures. They are:

Prior Knowledge: How can the learning environment draw upon students' past experiences and knowledge, while facilitating their ability to break free from it? It is common for students to draw on their prior knowledge and develop inconsistent mental models of new concepts (Vosniadou, 2001). Most students' prior knowledge of quantum mechanics is based on classical mechanics, and students often mix classical concepts with quantum ones. Helping students break free of their classical preconceptions is a major challenge as quantum concepts often contradict our everyday experiences and the laws of classical mechanics.

Serious yet Playful: How can we create a learning environment that is both scientific and immersive; serious yet playful? Play is often considered to be in opposition to 'serious' scientific study. To be effective, educational science games should not only be scientifically accurate but also immerse students in a space of engaging play. The challenge lies in meaningfully integrating the characteristic features of games, such as game mechanics, with scientific concepts.

Character Design: How can we develop a game character that is relatable across the gender spectrum but resists reinforcing gender stereotypes? Both science and gaming cultures have a large gender disparity (Hill, Corbett, & St Rose 2010; Martin & Rafalow, 2015; Ray, 2004). While the cause of this problem is much larger than any single environment, steps can still be taken to actively avoid practices that reinforce such a disparity. For example, game characters are often designed with young white male audiences in mind and tend not to be mindful of the diversity of players. Yet, relatable game characters can make players significantly more invested in the game (Kinzie & Joseph, 2008; Littleton, Light, Joiner, Messer, & Barnes, 1998). The challenge lies in designing characters that are relatable to players but do not reinforce stereotypes.

As a response to the first challenge, we designed the game levels to facilitate a comparative understanding of prior and new knowledge. To address the second challenge, we designed an integrated environment, combining scientific concepts and diagrams with game mechanics. This approach also informed our integration of tutorials into the game environment. For the third challenge, we designed a robot character with subtle customizable features.

Approaching these challenges required an interdisciplinary team along with strategies to support effective collaboration. Our strategies include establishing a core team, using ongoing evaluation as a way to help new team members craft their own design roles, and developing a series of concept maps that serve as blueprints for quantum mechanics concepts included in the game.

Our goal as designers was not to "fix" these challenges but to use them as opportunities to evoke a richer understanding of educational game design. For this, we had to position ourselves not only as educators, but also as learners. We did not approach *Particle in a Box* aiming to apply a fixed preconceived notions of games, learning, and science. Rather our understanding evolved with the problems and situations we faced during design similar to the ethos of design illustrated by Meyers, Nathan, and Tulloch (2019) in their design of a picturebook app *Pīsim Finds Her Miskanow* in collaboration with the O-Pipon-Na-Piwin Cree community.

Previous Work

We have outlined the details of our rationale and purpose for making the game, its evaluation, and other relevant background research in prior publications (Anupam, Gupta, Naeemi, & JafariNaimi , 2018; Peng, Dorn, Naeemi, & JafariNaimi, 2014; Tople et al., 2015). One broad design decision is important to note here. Why design a game? Why not design an interactive visualization or a simulation? Our decision to design a game was not based on the gamification trend in education which is arguably flawed and can be misguided due to its focus on extrinsic motivation and risk of habituating students to learning only when they are "rewarded" (Conway, 2014; Dichev & Dichev, 2017). Rather, we decided to design a game given that one of the key characteristics of quantum mechanics is its probabilistic nature, and the best way to understand this nature is to experience it over and over. The repetitive nature of gameplay is particularly suitable for understanding various probabilistic quantum phenomena.

Our goal for *Particle in a Box* is for it to be used as a supplement for teaching as opposed to a stand-alone self-explanatory piece that replaces formal instruction.

Textbooks can cover a large amount of material in detail but are inherently limited in their ability to depict the complex and dynamic features of real-world systems (Redish, 2000). They depend on static depictions of concepts through text, diagrams, and formulas. Games can supplement textbooks by enabling interactions with dynamic visualizations through which students test hypotheses and receive immediate feedback. We designed the four levels of the game to be playable in 10–20 minutes, so as to give teachers enough time to prepare students and discuss the game in class. We formally evaluated the game with fourteen undergraduate students enrolled in an electrical engineering class that involved introductory quantum mechanics (Anupam et al., 2018) in addition to ongoing evaluations built into our process. Most students who played the game had little or no prior experience with quantum mechanics. The formal evaluations consisted of one questionnaire before and one after the game. Each of these questionnaires consisted of multiple-choice questions relevant to classical and quantum mechanics along with space for written explanations. The key findings from our evaluation indicate that students demonstrated an improved understanding of the concept of probability and of the differences between classical and quantum mechanics. Overall, most students felt more comfortable with quantum mechanics than prior to playing the game.

It is important to note that *Particle in a Box* is designed to be part of an undergraduate curriculum and as such requires some prior knowledge of the scientific concepts. Accordingly, it is neither intended nor possible for this paper to serve as the basis for understanding quantum mechanics. We reference those concepts only to the extent that is required for demonstrating the design process especially as related to the challenges outlined earlier. Interested readers are directed to Griffiths (2005) and Ananthaswamy (2019)

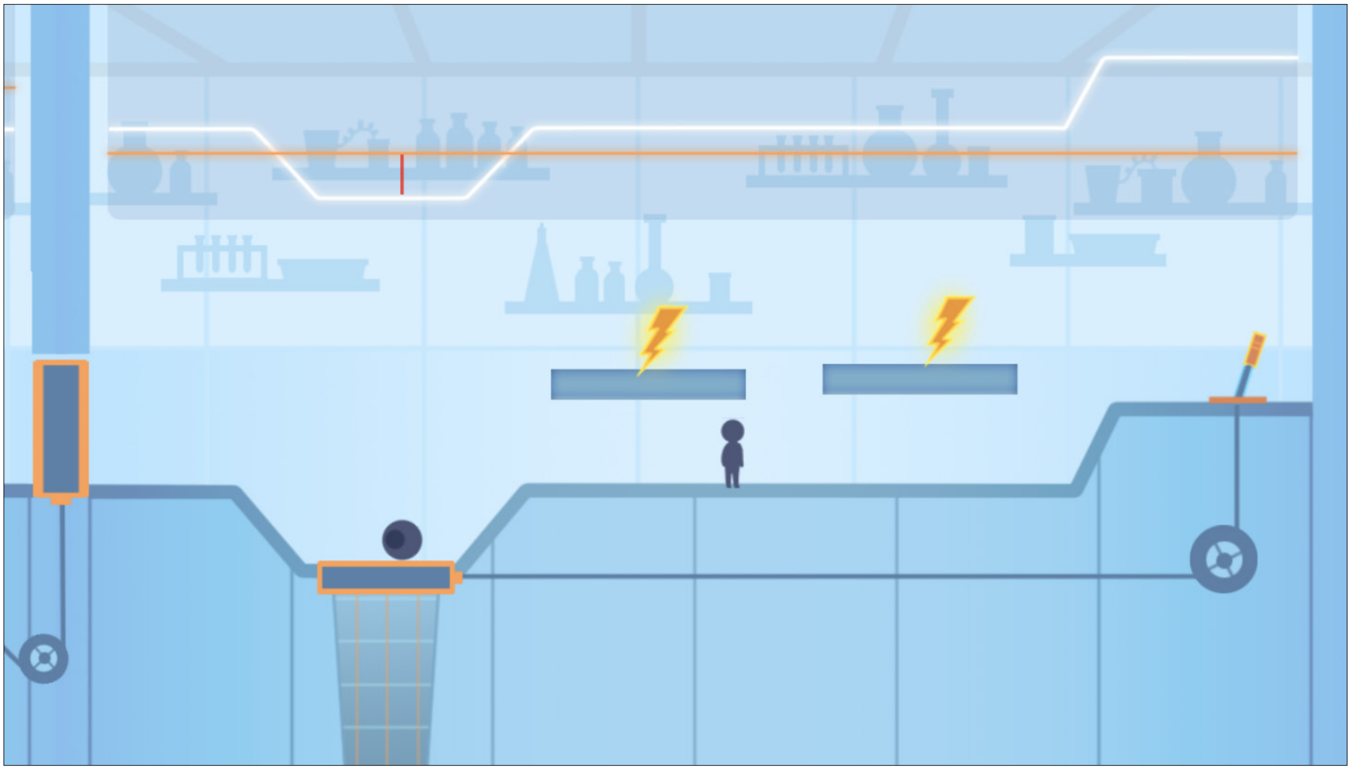

FIGURE 2A. Classical environment: The classical world is depicted by an abstracted lab setting with familiar scientific equipment in the background.

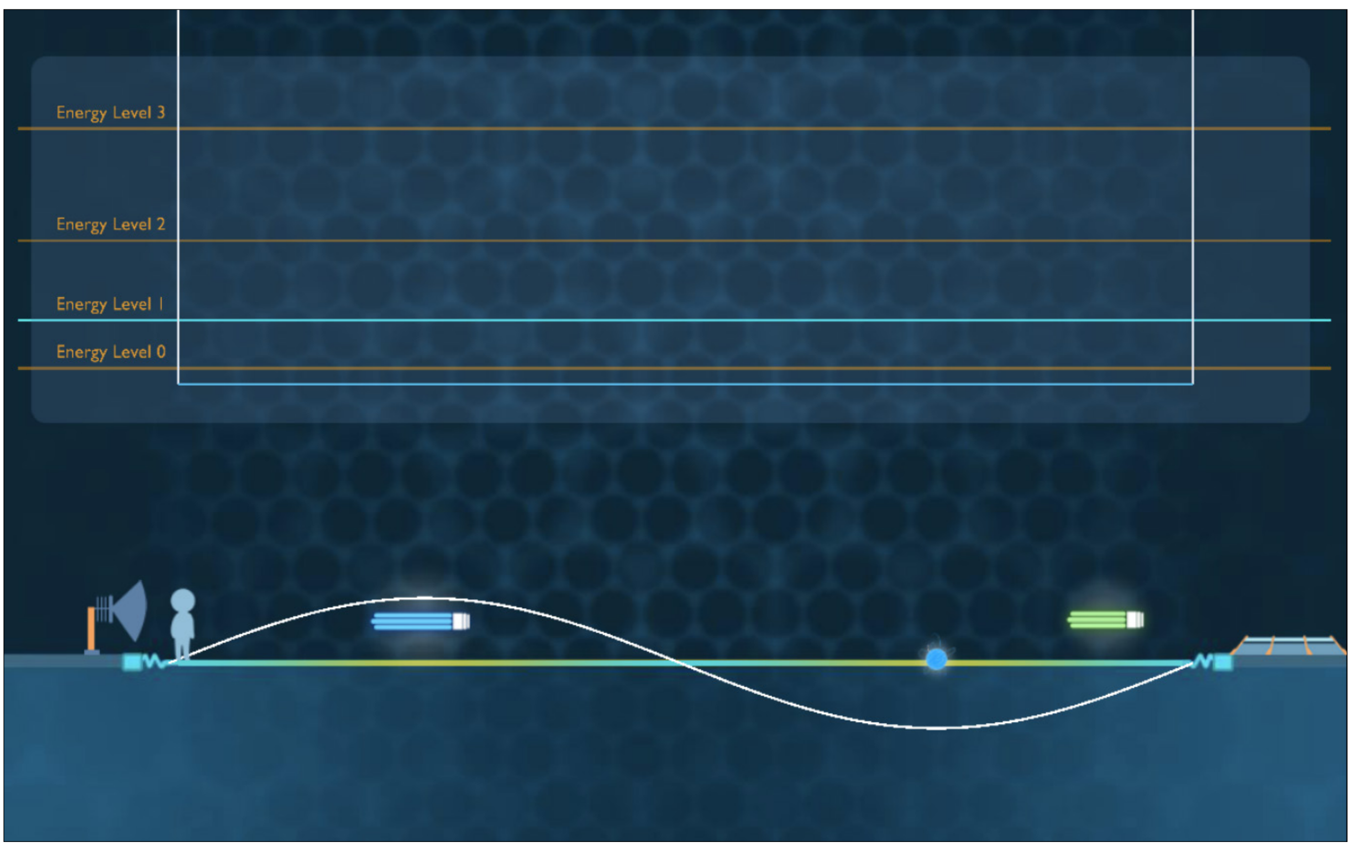

FIGURE 2B. Quantum environment: The quantum world is depicted in a darker tone to convey a sense of mystery and wonder. The background depicts an atomic environment inhabited by quantum phenomena.

for excellent introductions to quantum mechanics. In what follows we examine the overarching challenges in detail.

DRAWING UPON AND BREAKING FREE FROM PRIOR KNOWLEDGE

Students do not learn about a new subject on a "blank slate" (Bransford, Brown, & Cocking, 2000). Rather, learning takes place through the interaction between new and prior knowledge. However, this process can result in misconceptions if not addressed through instruction (Bransford et al., 2000; Redish, 2000). For example, when children who think the earth is flat are told that it is round, they envision it as a pancake (Vosniadou, 2001). This brings us to our first challenge:

How can the learning environment draw upon students' past experiences and knowledge, while facilitating their ability to break free from it?

Most students' prior conceptions of quantum mechanics are rooted in classical mechanics (Johnston et al., 1998; Mashhadi, 1995; Singh, 2001). The theory of classical mechanics was developed through contributions made by multiple scientists in 16th and 17th centuries such as Galileo Galilei, Johannes Kepler, and most notably Isaac Newton who formulated the laws of motion. Central to these laws is the assumption that the position and momentum of an object can always be precisely measured and predicted. These laws adequately explain the motion of macroscopic objects and map well with our everyday experiences of phenomena. However, they do not explain the behaviors of particles at the atomic scale. These behaviors are better explained by theories of quantum mechanics developed in the 20th century. Quantum mechanics deals with some of the same fundamental properties of objects as in classical mechanics such as energy, position, and momentum. However, it radically challenges the classical interpretations of these properties. For example, in a quantum system, we can never know a particle's precise position and momentum at the same time. We can also never predict with certainty where a particle will be at a future time. We can only calculate the *probability* of finding the particle at various positions. Further, particles exhibit wavelike properties similar to light, where they can "spread out" over an area. Counterintuitive quantum phenomena like these require students to fundamentally re-envision assumptions and concepts that they know from classical mechanics.

As novice students have little or no familiarity with quantum phenomena, their ideas of particle behavior are constrained

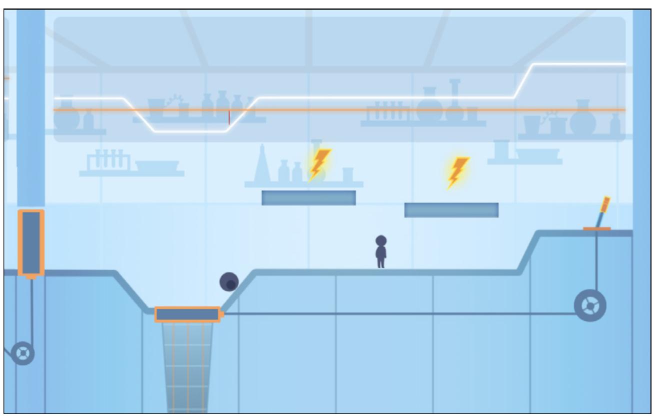

FIGURE 3A. In the classical world, the player observes the ball move along the ground.

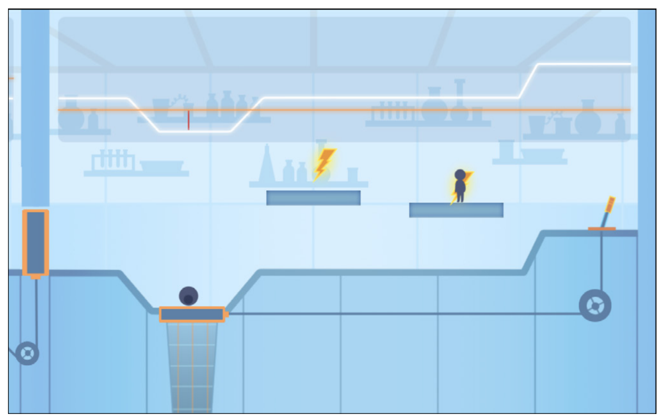

FIGURE 3B. The player collects energy sources (yellow bolts) while avoiding the ball.

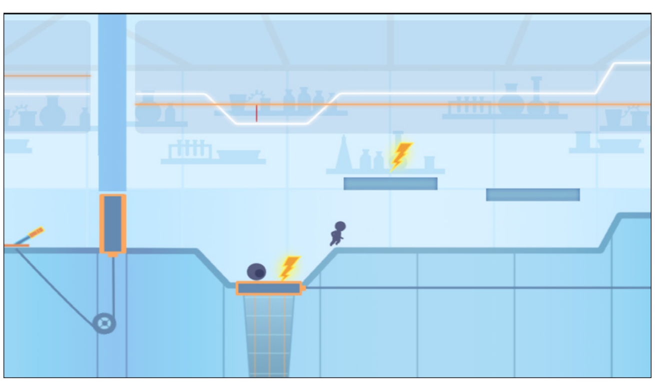

FIGURE 3C. After collecting a bolt, the player has to place it in the path of the rolling ball.

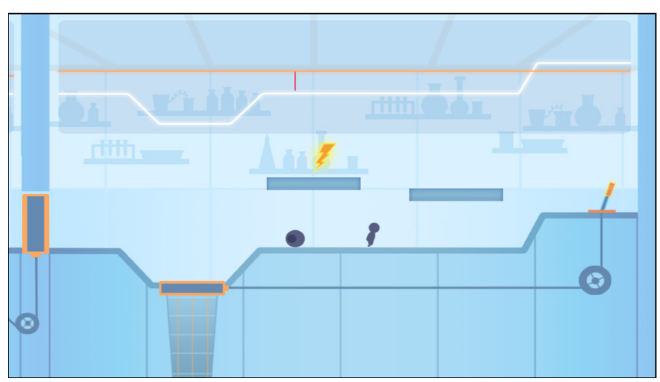

FIGURE 3D. The ball, on rolling over the bolt, absorbs it, causing its energy to increase.

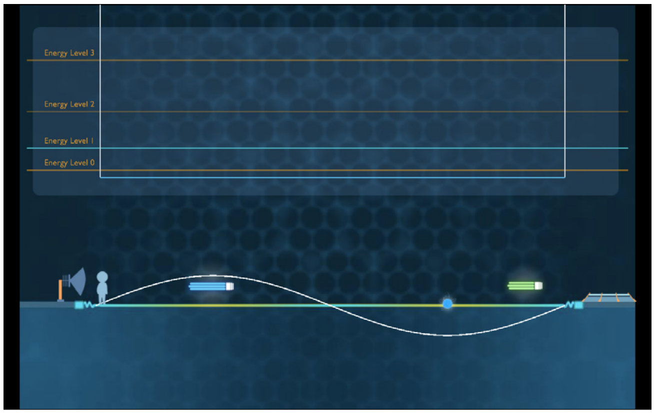

FIGURE 4A. In the quantum world, the player observes an electron (blue dot) appear along a wire according to a probability distribution.

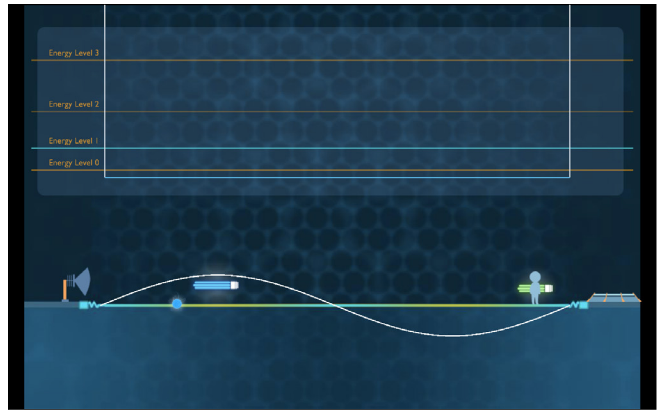

FIGURE 4B. The player collects energy sources represented by bulbs of different colors, while avoiding the electron.

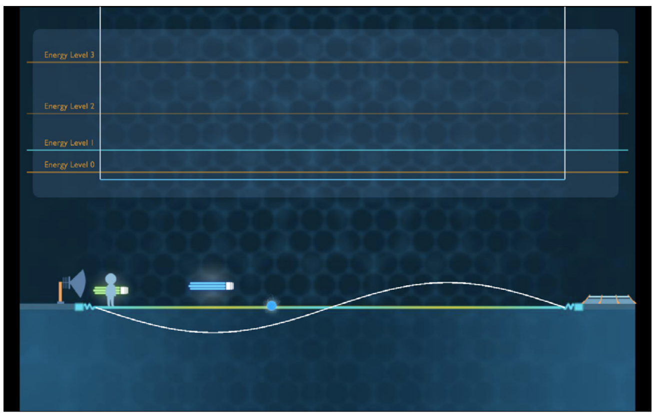

FIGURE 4C. After collecting the correct colored bulb (green bulb in this case), the player brings it to the lamp.

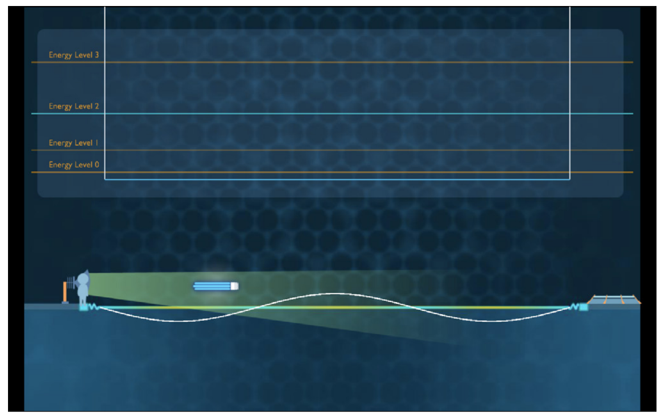

FIGURE 4D. The lamp shines the appropriate light onto the wire and changes the electron's energy and wave function.

to or adapted from classical mechanics. They find it difficult to understand that a particle's position can be inherently probabilistic and that the particle may not be in one definite position at a time. When confronted with information on the wavelike-nature of the electron, students often develop inconsistent synthetic models (Vosniadou, 2001) in which they mix their prior understanding with the new information. For example, they may think of the electron as a particle that moves along a wave instead of itself behaving like one (Mashhadi, 1995). Simply telling students about these phenomena may not be enough. Students may need to experiment with these concepts to better understand them (Vosniadou, 2001).

Thus, one goal of the learning environment was to enable students to test their prior knowledge of classical mechanics against the new understanding they gained of quantum mechanics. In the following section, we discuss the key decisions we made in pursuit of this goal.

Comparative Understanding

We aimed to evoke students' understanding of classical mechanics and then challenge them to apply that understanding and correct it when faced with quantum mechanics. We made three key decisions towards this goal:

1. Distinguishing classical and quantum worlds
2. Designing the sequence of gameplay to build on and challenge prior knowledge
3. Setting game goals that highlight the differences between prior and new concepts

Distinguishing classical and quantum worlds

To ensure that students clearly understood the differences between classical and quantum mechanics, we divided the game into two worlds—one that followed the laws of classical mechanics (Fig. 2a), and another that followed quantum mechanics (Fig. 2b). This is in contrast to most other quantum mechanics games where the quantum laws are applied on classical objects such as Quantum tic-tac-toe (Goff, 2006), and Quantum Race (Chiarello, 2015). It must be noted that these games are not designed as learning environments but as entertaining experiences that involved some quantum phenomena. Although such games draw interest, they are not reliable environments for learning quantum mechanics partly because they take quantum concepts out of context. For example, the probabilistic state of a particle depends heavily on the physical system that it constitutes. Different quantum systems (such as differently shaped quantum wells) can result in different probabilistic states. However, these games treat the particle independently or in contexts far removed from any quantum well (like in tic-tac-toe). By juxtaposing classical and quantum concepts in the same environment, they risk encouraging the development of inconsistent mental models of quantum mechanics.

Separating the classical and quantum worlds served to prevent confusion between them. Our evaluations indicate that this strategy was largely successful. In the pre-test, most students applied their classical understanding to quantum mechanics questions. However, after playing the game, students successfully distinguished between classical and quantum concepts. Even when students did answer the quantum questions incorrectly, they chose those options that were variations of the correct quantum concepts, and not those belonging to classical mechanics.

Designing the sequence of gameplay to build on and challenge prior knowledge

The sequence of gameplay affords the opportunity to strategically build and challenge students prior knowledge. Most students' prior knowledge about the properties of objects, such as their position or energy, stems from their daily experiences and can be explained by classical mechanics. For example, classical mechanics predicts that any amount of energy given to a ball (say by heating or pushing it) will change its state (increase in temperature or movement). However, in quantum mechanics only certain amounts of energy given to the electron will increase its energy. This is because the energy of an electron is discrete, i.e., it can only possess specific values of energy such as 1 eV (electron-volt) and 3 eV, but nothing in between. Energy is usually supplied to the electron in the form of light. Light consists of discrete energy packets (photons) whose energy depends on their color. All photons of the same color have the same energy. Only those photons that are the correct color will have the exact amount of energy that can be absorbed by the electron. For example, if the possible energies of an electron are 1 eV and 3 eV, and it is currently in the 1 eV state, then it will only absorb light whose photons have 2 eV of energy (orange light) to get to the 3 eV state.

Playing the quantum world after the classical one encourages students to apply classical conceptions to quantum phenomena. This results in temporary failure which induces a recognition of the incompatibility of classical and quantum mechanics. For example, our evaluations indicated that students initially believed any color of light will increase the electron's energy. However, after observing that green light is ineffective and that red light is needed in the first game level, they learned that the electron's energy is unlike that of a ball and must be treated differently. Failure enabled them to break free from their prior understanding (Posner, Strike, Hewson, & Gertzog 1982) and build a more robust mental model of the behavior of the electron.

Setting game goals that highlight the differences between prior and new concepts

To better highlight the differences between classical and quantum mechanics, we designed both worlds to have a common goal: to increase the particle's energy. Energy is a concept that is shared by classical and quantum mechanics but functions differently in each. In classical mechanics, a ball's energy is continuous, i.e., it can possess any amount of energy. In quantum mechanics, however, an electron can only possess discrete values of energy (such as 1 eV and 2.5 eV but nothing in between) depending on the quantum system. Particles in the two worlds also behave very differently when their energy is changed. For a ball, an increase in total energy can imply faster motion and/or movement to a greater height. However, for an electron, an increase in energy will result in a change in its wave function and consequently its position probability distribution (Fig. 6a and b). Choosing the goal of the game to be that of raising the particle's energy in each of the worlds offered an effective way of illustrating the differences between particle behaviors in classical and quantum worlds.

SERIOUS AND PLAYFUL

The key to designing effective educational games lies in meaningfully integrating play with learning (Prensky, 2003, Arnab et al., 2015, Lameras et al., 2017). This implies that learning and play should support each other. Learning new concepts should aid the player in their actions in the game. Conversely, performing actions should help the player apply and refine their understanding of those concepts. Progress in the game should be contingent on learning and applying what has been learned. Limited consideration of the connection between player actions and concepts can result in "chocolate-covered broccoli" games that overlay playful graphics onto the subject matter without improving either student learning or engagement (Bruckman, 1999).

For example, in *Math Blaster*, students answer arithmetic equations such as "5+3=?" to power up a blaster gun which they can use to shoot floating space trash (Eckert & Davidson, 1987). Through this design, *Math Blaster* aims to motivate students to practice addition and subtraction. The primary problem with this approach is that the actions of the player are disconnected from the concepts of addition and

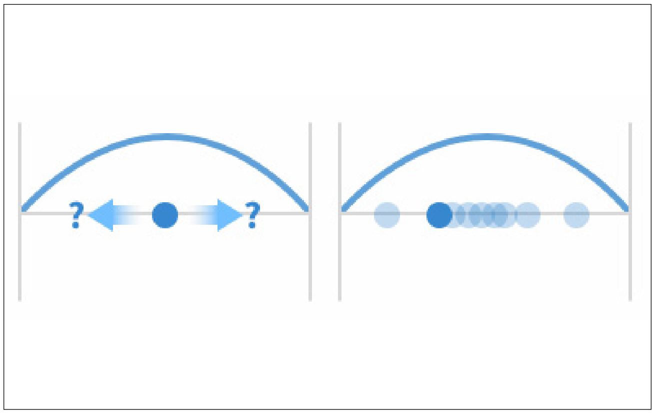

FIGURE 5A. Wave function: This diagram illustrates the connection between the wave function (blue curve) and the electron's probability distribution (faded blue dots).

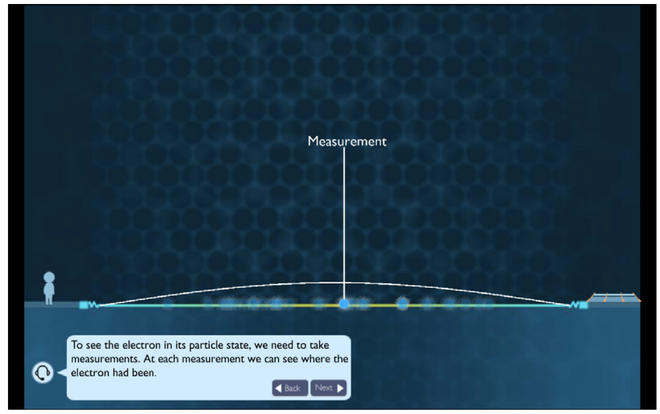

FIGURE 5B. Wave function in the game: The player observes consecutive measurements of the electron's position. The electron (blue dot) appears each time it is measured and leaves a trace behind, dynamically creating the probability distribution.

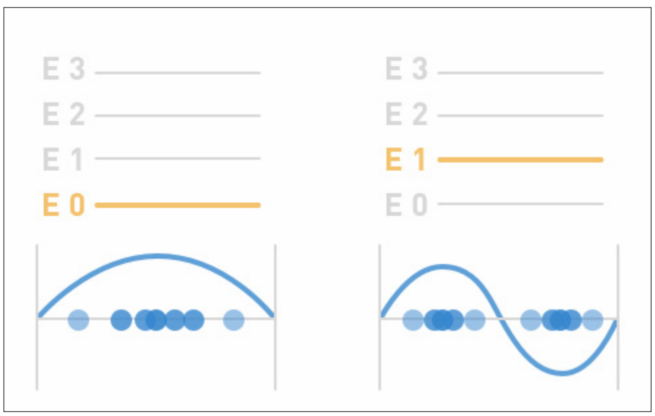

FIGURE 6A. Energy levels: A change in the electron's energy level adds more peaks/nodes to the wave function (blue curve). This change is represented in two sequential static figures.

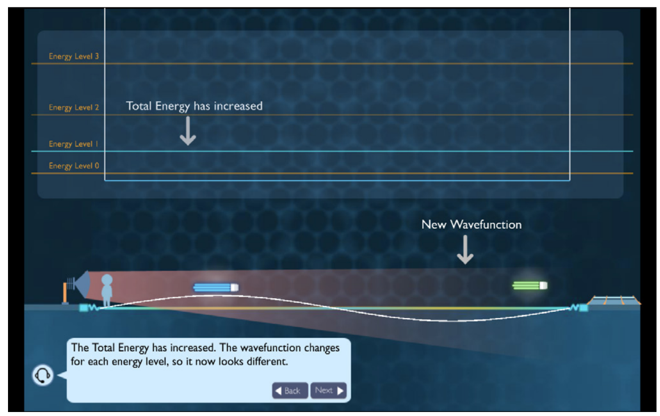

FIGURE 6B. Energy levels in the game: When the lamp shines light, it changes the electron's energy level and the wave function simultaneously. The system can be observed in its natural dynamic state.

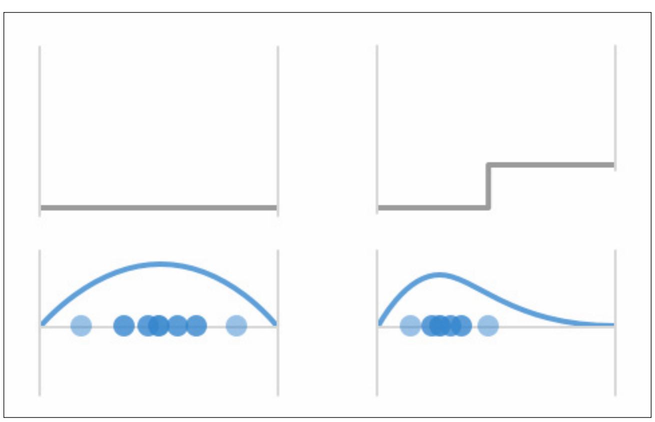

FIGURE 7A. Potential profile: A change in the potential profile (grey line) changes the wave function (blue line).

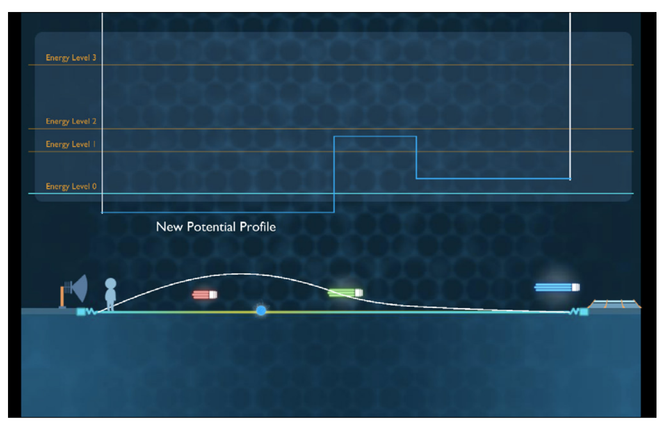

FIGURE 7B. Potential profile in the game: Players enter a new quantum level with a different potential profile. This new potential profile results in a new wave function and thus a new probability distribution of the electron.

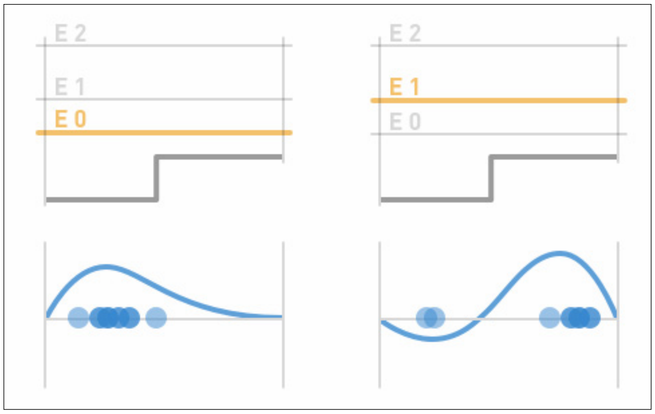

FIGURE 8A. Combined conceptual system: In the combined system diagram, the potential profile, and energy levels are drawn on the same scale and axes. Their relative positions together affect the shape of the wave function.

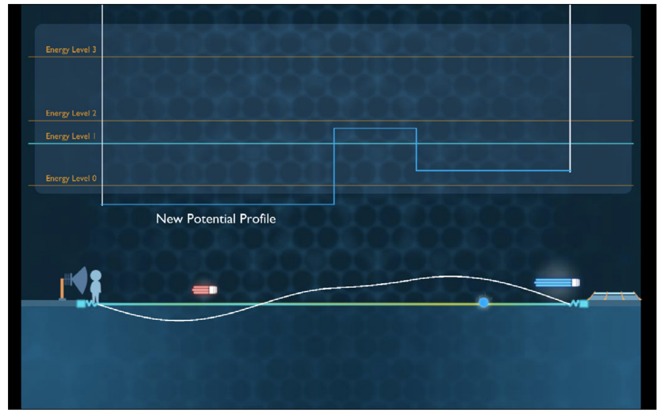

FIGURE 8B. Combined system in the game: The combined effect of the potential profile and energy levels is visible on the wave function each time players increase the electron's energy in a new quantum level.

subtraction. Shooting space trash requires students to focus on their motor skills, such as reflexes and accuracy, and is unrelated to adding and subtracting. Even though the action of shooting and the concepts of addition and subtraction are "integrated" in the sense that they occupy the same space in the game, this integration is not *meaningful.* Adding and subtracting better does not help students shoot better. Shooting better does not help students understand addition and subtraction better. Further, the arithmetic equations are out of context and miss the opportunity to engage students with the meaning and relevance of adding and subtracting. For example, students have to answer an abstract equation such as "5+3=?" instead of counting and moving say 5 apples to a basket of 3. Overall, the game functions as a digital drill-and-practice sheet instead of an experiential learning environment.

Meaningfully integrating play and learning is challenging as one can often override the other. Improving the learning environment can come at the cost of engagement. For example, in *Math Blaster*, if instead of shooting space trash, students were required to count, move, and sort pieces of space trash into bins of different capacities, it would support learning addition and subtraction better. However, this might be less engaging for some students than shooting. Conversely, improving engagement can limit learning. For example, *Math Blaster* may become more engaging if instead of typing the answer to the equation, students had to shoot it as it floated in space, just as they shoot space trash. However, this could frustrate students who know the answer but find it difficult to aim and shoot quickly and consequently limit their learning. This brings us to our second challenge:

How can we create a learning environment that is both scientific and immersive; serious yet playful?

Integrated Environment

To create an environment that is both serious and playful, we adopted three main strategies:

1. Integrating interactive scientific visualizations as part of the game environment
2. Integrating game mechanics with concepts
3. Using tutorials to scaffold students into the game environment

Integrating interactive scientific visualizations as part of the game environment

Quantum mechanics, unlike classical mechanics, cannot be perceived directly in daily life. One cannot perform an experiment at home with an individual electron like one may do with a ball. Analysis of quantum phenomena is primarily limited to mathematical and visual models. Text, diagrams and formulas in textbooks comprise the primary sources of study for most undergraduate students, but they are limited in their capacity to represent the dynamic nature of quantum phenomena. To experientially engage students with quantum mechanics we designed a learning environment that transformed the formulas and diagrams of textbooks into interactive visualizations. We adopted diagrams of key concepts namely the wave function, energy levels, and the profile of potential energy (Fig. 5–8) from an introductory quantum mechanics textbook (Griffiths, 2005) and designed them to respond to player actions. For example, in the quantum world, if the player transports the correct light bulb to a lamp, it will shine a light that can change the energy level and wave function diagrams (Fig. 6b). Students can thus observe the dynamic behavior and response of the quantum system to their actions.

Integrating game mechanics with concepts

The actions that players repeatedly perform in a game, such as running, jumping, and picking up items are called game mechanics (Salen & Zimmerman, 2006). By meaningfully integrating these repetitive actions with scientific concepts, designers can take advantage of game mechanics to facilitate engaging play and focused learning. We designed each game mechanic to support the learning of a key concept.

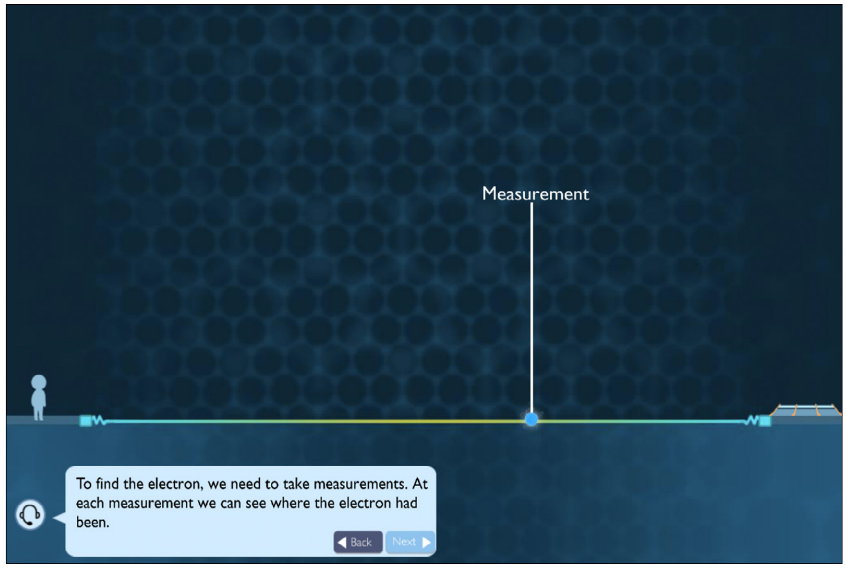

FIGURE 9. Measuring an electron collapses the superposition state of the electron.

Game Mechanics in the Quantum World

Game mechanics in the quantum world were designed to support the learning of three main concepts: measurement, the position probability-wave function relationship and the wave function-energy relationship. These are foundational concepts in quantum mechanics that contradict our daily experiences and therefore present major challenges to learning.

First, we present a brief description of a measurement. A measurement in quantum mechanics is the act of "observing" a particle in a quantum system. One of the peculiar features of quantum systems such as an atom or a quantum wire (a wire that is extremely small in diameter) is that inside them, the electron exists simultaneously in multiple possible positions, i.e., a state of super-position (Fig. 9). For example, inside a quantum wire, an electron can simultaneously occupy all points in the wire. However, the act of measurement triggers a collapse of this superposition, leading to the temporary localization of the electron in only one small region. The laws of quantum mechanics dictate that this region cannot be predicted beforehand and that each measurement will collapse the electron into an unpredictable region. To visually represent measurement in our game, we designed the electron to 'appear' in the form of a bright blue dot on a quantum wire each time a measurement is taken. When the system is reset, the electron 'disappears' into the wire until the next measurement is made.

To support the learning of the concept of measurement, we designed a game mechanic in which the player needs to avoid the electron when it is measured. Measurements are taken automatically and periodically and result in the electron "appearing" and "disappearing" in different spots like an unpredictable "foe." If the player comes in contact with the electron, they lose, and their character is sent back to the starting position. By choosing the electron to be the "foe," the game directs players attention to the electron's behavior and requires them to observe and understand the concept of measurement. Each time players fail, they experience the unpredictability of the electron's measured position. This knowledge in turn aids the player in formulating a strategy to avoid the electron.

Second, we describe the position probability-wave function relationship. While the position where an electron will be measured cannot be predicted beforehand, it is still probabilistic, i.e., some positions are more likely than others. The relative probability of measuring an electron at each point in a quantum system is illustrated by the wave function curve. The higher a point on the curve, the more likely the electron will appear at the corresponding position under it on the wire. For example, in Fig. 5a, the wave function indicates that the electron is more likely to be measured in the center region than the regions closer to the ends.

To support the learning of this position probability-wave function relationship, the game visualizes the wave function over the quantum wire. By observing the shape of the wave function, players can infer the relative probability of the electron appearing in different regions of the wire, strategize their movement across it, and maximize their chances of avoiding the electron. The more they play, the more closely they will be able to experience the relationship between the wave function and probability.

Finally, we discuss the wave function-energy relationship. The shape of an electron's wave function changes with its energy. Increasing the energy of an electron requires one to shine light on it of the appropriate color. The higher the energy of the electron, the more peaks and nodes its wave function possesses (Fig. 6a). A "node" is a point where the probability of an electron to appear upon measurement is zero.

To support the learning of this wave function-energy relationship, we devised a game mechanic in which players must transport appropriately colored light bulbs that are scattered across the wire back to a lamp. When the right color bulb is received by the lamp, it shines light of the same color and increases the energy of the electron. If an incorrect bulb is received, the lamp does nothing. As the electron's energy increases, so does the number of nodes in its wave function. With more nodes, the player has more "safe spots" on the wire to stand on as they move across it, making subsequent play easier. This game mechanic, therefore, requires players to understand what colored bulb will work, observe the current wave function, and then strategize their path to transport it (Fig. 4).

Game Mechanics in the Classical World

Game mechanics for the classical world were chosen to reinforce students' preconceptions of position, energy, and their relationship.

'Position' in classical mechanics is deterministic, i.e., particles can only exist in one position at a time and their future positions can be predicted based on their current motion. To reinforce this concept, we devised a game mechanic in which players have to avoid a moving ball. If players come in contact with the ball, they lose and have to restart. The ball provided a simple way to illustrate the laws of classical mechanics as it does not require any external agent (other than gravity) to move. The player can always observe and predict the motion of the ball and know when to jump over it.

'Energy' in classical mechanics is continuous, i.e., particles can possess any amount of energy. To reinforce this concept, "energy bolts" were introduced as an item that the player collects and places in the path of the ball. Upon rolling over a bolt, the ball absorbs the bolt and increases its own energy. It does not matter which energy bolt the player chooses as the ball can absorb them in any order, unlike the electron in quantum mechanics which only absorbs specific colors depending on its current energy level.

When the energy of particles in classical mechanics increases, they can move to greater heights (an increase in potential energy) and/or move faster (increase in kinetic energy). In the game, this is reflected by the ball moving faster and reaching greater heights when it absorbs an energy bolt. The player needs to observe and respond to the changes in the motion of the ball each time they feed it a bolt. To complete

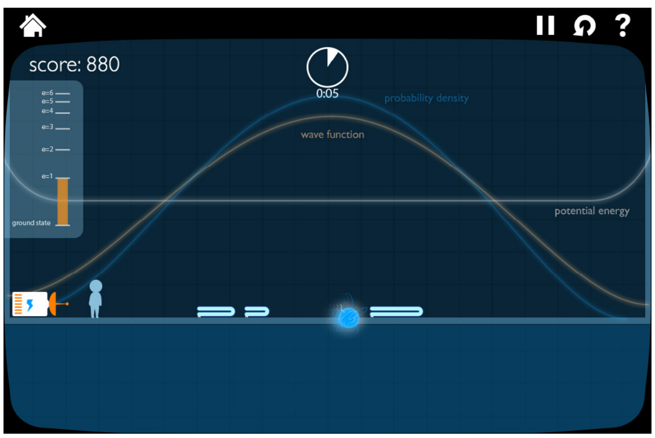

FIGURE 10A. The first iteration of the quantum world used light bulbs of varying lengths but the same color to depict different amounts of energy.

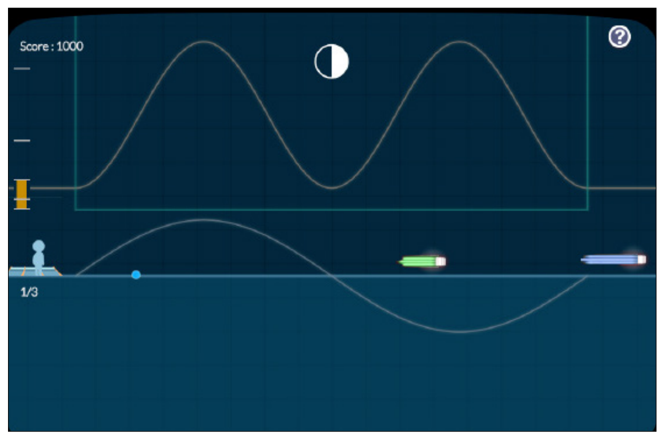

FIGURE 10B. The second iteration of the quantum world used light bulbs of varying lengths and colors to depict different amounts of energy.

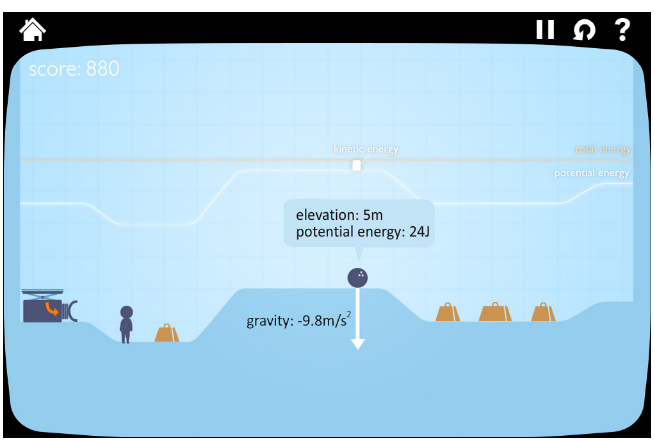

FIGURE 11A. The first iteration of the classical world used standard weights to depict different amounts of energy.

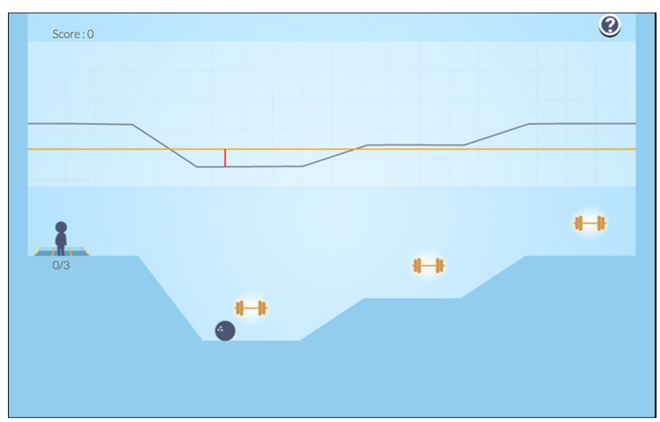

FIGURE 11B. The second iteration of the classical world used gym weights to depict different amounts of energy.

the level, the ball must have sufficient energy to reach and push a lever that is located at a higher point. This completes the classical world and opens up the door to the quantum world. Overall, in both worlds, gameplay progresses as the player observes the behavior of the particle (ball or electron), avoids it, collects the energy sources (bolts or bulbs), and supplies them to a lamp or the ball to increase the particle's energy. This energy increase changes the behavior of the particle and the cycle repeats. In the classical world, the ball rolls faster and reaches greater heights. In the quantum world, the electron's wave function changes. This results in more 'nodes' or safe spots where the player can stand without fear of being hit by the electron, and more peaks where the electron appears more frequently. The player must try to understand the particle's new behavior as they collect the remaining energy sources. These feedback loops provide a dynamic learning experience that drives the player towards learning basic concepts of quantum mechanics. The key concepts and gameplay support each other. Students observe the working of the system and use that knowledge to engage with the game environment.

Previous Iterations

In the initial iterations of the quantum world (Fig. 10a and 10b), the bulbs were all kept the same color. Differences in energy were denoted by the length of the bulb. Visually, this missed the opportunity to reinforce the relationship of color and energy. Further, the game contained two overlapping graphs (wave function and probability density) that depicted the same concept—the electron's probability. Although both graphs are commonly used in textbooks, showing them together caused confusion and was deemed redundant in our pilot tests. The game also initially kept a score which increased each time the player picked the correct bulb and decreased when they did not, but it went unnoticed in the pilot tests and was subsequently removed as it did not contribute to learning or play. Finally, the energy levels were initially presented separately on the left. This was done to draw attention to them as they represent the target that the player has to achieve. However, this depiction was in disagreement with standard textbooks where energy levels are superimposed on the potential energy graph to enable comparison (Griffiths, 2005). In initial iterations of the

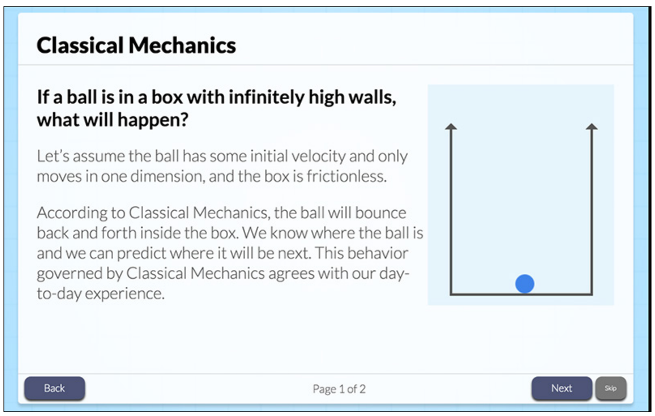

FIGURE 12A. The first iteration of the classical world tutorials presented 3–4 pages of text.

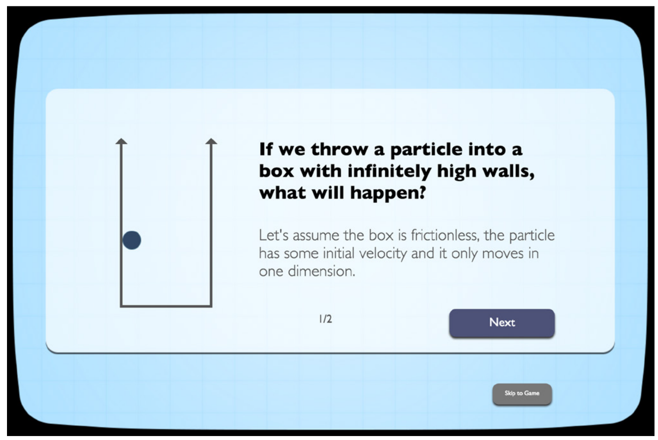

FIGURE 12B. The second iteration of the classical tutorial included a shorter version of text.

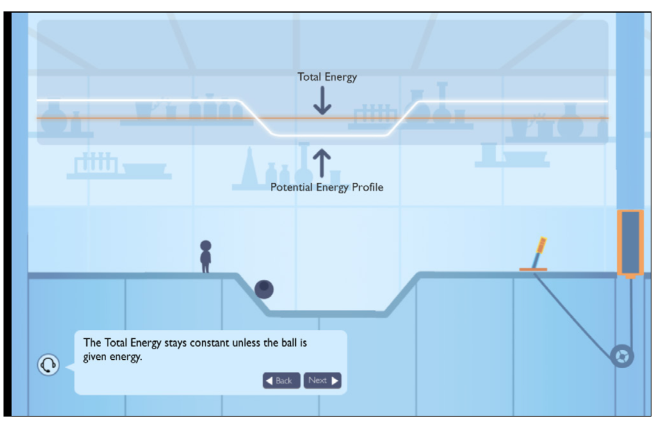

FIGURE 12C. The current iteration of the classical tutorial employs arrows and text as part of the game environment.

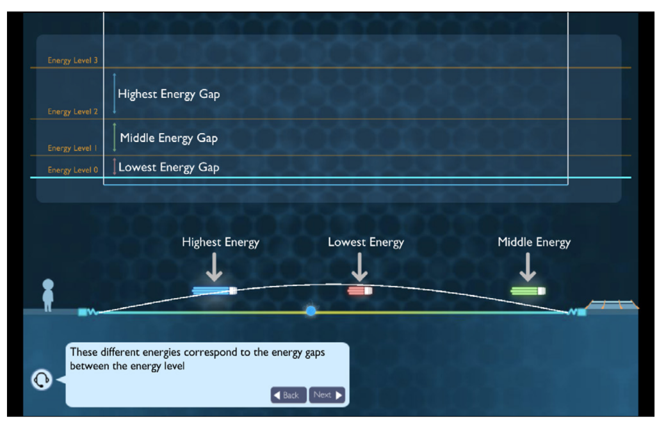

FIGURE 12D. The current iteration of the quantum tutorial is similar to the classical tutorial but uses lighter colors for visual contrast.

classical world, the player was required to pick up "weights" and bring them to a machine that increased the ball's energy (Fig. 11a and 11b). However, pilot tests on the game revealed that players did not understand why the ball's energy increased because there was no visual connection between the machine and the ball. Further, the "weights" were not read as items that increased the ball's energy and appeared to the students as "suitcases." The problem persisted even upon the use of a different visual metaphor of "gym weights" in the subsequent iteration. Ultimately, in the present iteration, the weights were replaced by the "bolts" to be supplied to the ball directly to mitigate the above problems.

Using tutorials to scaffold students into the game environment

Given the abstract nature of quantum concepts and the educational goals of the game, it was necessary for the game to include tutorials that familiarized the players with the game environment. In earlier versions, the tutorials were 3–4 pages of text presented before the beginning of each level (Fig. 12a and 12b). However, in our evaluations, students recounted that their experience of the tutorial resembled that of an interactive textbook and interfered with their game experience. Further, as the tutorials isolated learning from application, students struggled to remember and identify the connection between subject-matter and gameplay.

Most current games design tutorials as scaffolded game levels where different areas of the game environment are highlighted by arrows and text boxes. Our latest iteration borrows from this approach. We present the tutorials as a series of small challenges at the start of each world in the game environment itself (Fig. 12c and 12d). The tutorial level builds up and explains the environment and the concepts step-by-step. The player is guided to perform a necessary game action (such as bringing an energy bolt to the ball) before they can proceed to the next action. Upon completion of the tutorial, the player is left to complete the remaining level on their own. Through this strategy, players are given enough support at the beginning to start playing the game right away. Simultaneously, it also leaves room for players to discover and experience the concepts on their own.

CHARACTER DESIGN

Game characters play an important role in immersing players into the game environment (Adams & Dormans, 2012) partly because they allow players to inhabit roles they otherwise cannot (Barab, Gresalfi, & Ingram-Goble., 2010). The effect of character design on learning is difficult to isolate as it is intertwined with environmental, social, and personal factors and differences in subject-matter. While some studies have found correlations between specific character attributes such as warm colors or joyful expressions and positive emotions (Plass et al., 2019) and between positive emotions and learning (Um et al., 2012, Loderer, Pekrun, & Lester, 2018), the generalizability of these findings is limited. Attentiveness to the design of characters in educational games is especially important given the underrepresentation of women and minorities in STEM fields (Hill et al., 2010) that constitute an important audience of games such as *Particle in a Box*.

Game characters, however, can reinforce social and cultural stereotypes. Common examples include the the sexualized portrayal of women in *World of Warcraft* and the "damsel in distress" trope exemplified in *Super Mario Bros*, where a helpless princess must be rescued by a male protagonist. Such depictions not only reinforce problematic stereotypes but they also shape the makeup of the gaming community that suffers from a well-documented lack of diversity (Summers & Miller, 2014).

Players appear to relate more to characters similar to them (Kinzie & Joseph, 2008). Therefore, some argue that it is desirable to craft characters that are representative of players. However, this can also inadvertently reinforce subtler stereotypes. For example, smooth shapes and brighter colors are often associated with femininity, whereas more rigid shapes and darker colors are often associated with masculinity. Characters that exemplify such stereotypes can cultivate a sense of what characteristics are "appropriate" for a given gender or social identity. Younger and more impressionable players may even transfer these associations into their daily lives. For example, they may assume that pink is a "girly" color and that if a boy wears a pink shirt, then something is "wrong" with him. Consequently, subtler stereotypes are important to be challenged, even though they may be more difficult to be identified and addressed.

At the same time, one cannot simply design a feminine character with rigid shapes to "break a stereotype". Such a design may reinforce the false notion that only women who display "masculine" characteristics are successful in science. Decisions about the character design should not fall into the binary of "stereotypical" and "counter-stereotypical" or "masculine" and "feminine" as each enforces a particular view of gender. Instead, what is needed is to challenge any such gender binaries altogether (Subramaniam, 2014; Butler, 2011). These issues point to the third challenge:

How can we develop a game character that is relatable across the gender spectrum but resists reinforcing gender stereotypes?

Our first approach to this challenge was to create an abstract character with few expressive details (Fig. 13). We reasoned that a minimalist character design would limit its association with any particular identity. Players could project any identity on to it due to its lack of identity-specific features. We named this character 'psi' after the Greek symbol 'ψ' which represents the electron wave function in quantum mechanics and is also not associated with any gendered names to the best of our knowledge. However, our evaluations indicated that in spite of having child-like proportions and relatively

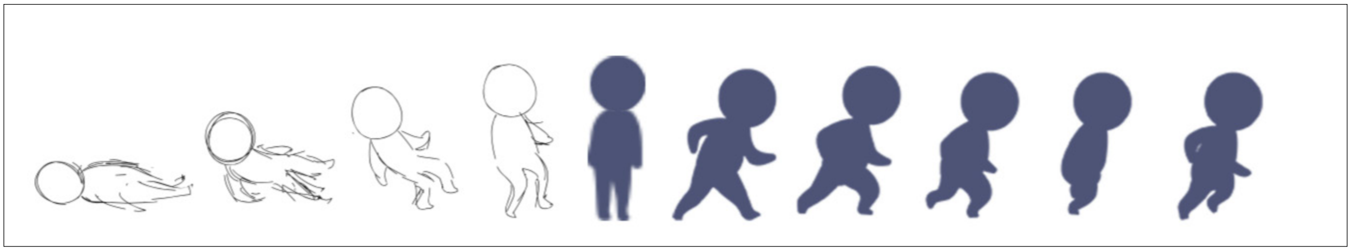

FIGURE 13. Our initial abstract and minimalist character design was perceived as male.

FIGURE 14. A variety of character designs were developed that lacked identity-specific features.

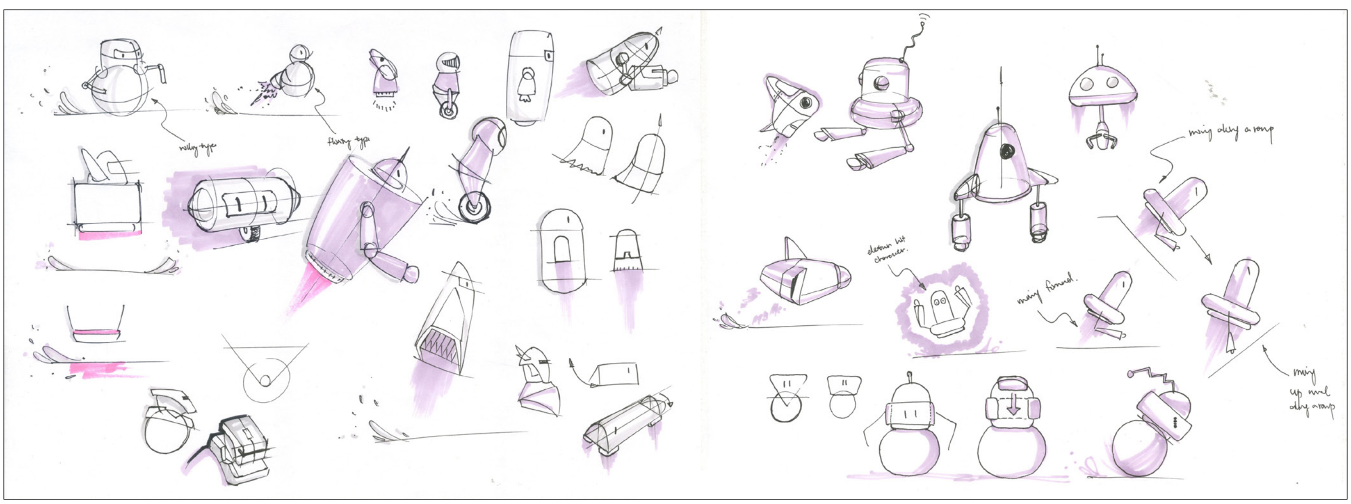

FIGURE 15. Robots were chosen as a working character template and several variations were made.

abstract embodiment, the character was interpreted as male. Additionally, the characters intentions were not clearly understood. Why was it moving around in the quantum world? What did it want to do? The abstractness and the lack of any context or story associated with the character left players without any special attachment towards it.

A human-like character necessitates a particular embodiment (e.g., age, gender, race) making it difficult to account for diverse demographics. One way to address this is to make customizable human characters. However, such a character would still be limited by customizable features such as accessories, clothes, and styling features.

The second possibility that we explored was to design non-human characters. Although no character design can be free from assumptions and bias, we posited that human characters amplify biases such as gender and race more than non-human characters. Our initial explorations of non-human characters consisted of animals, objects, robots and even wisps of energy (Fig. 14). Compared to other options the robot was simpler to explain as a character that can move around in the quantum world (like a nanobot). We hypothesized that players would be more willing to suspend disbelief and accept a robot in the quantum world than any other character. This is because robots are frequently referenced in popular culture (e.g., in science fiction series like *Star Wars*), where they perform activities that humans usually cannot do. Our current design (Fig. 17) was perceived as being similar to the "BB-8" robot in *Star Wars* during our initial pilot test. This made adding features to the character much simpler as they would just be accepted as "something robots can do."

However, robots are not free from being perceived as gendered. For example, robots such as "EVA" in the movie Wall-E are perceived as female (even if they are not intended to be gendered). Our current prototype aims to approach this issue by making the robot customizable. Instead of trying to design a character for every kind of player, players design their own robot at the start of each game. For example, players will have the option of choosing from different colors and shapes for the robot (Fig. 17). Customization can potentially increase players' engagement as they manipulate and evolve their characters over the course of the game (Lankoski & Bjork, 2008). Further, because the robot does not directly represent any clear demographic, it can afford to be limited in its customization options, unlike a human character. We posit that letting players design their own variation of the robot character would make it more relatable while avoiding the reinforcement of gender stereotypes. We will test the response to this feature in our next evaluation.

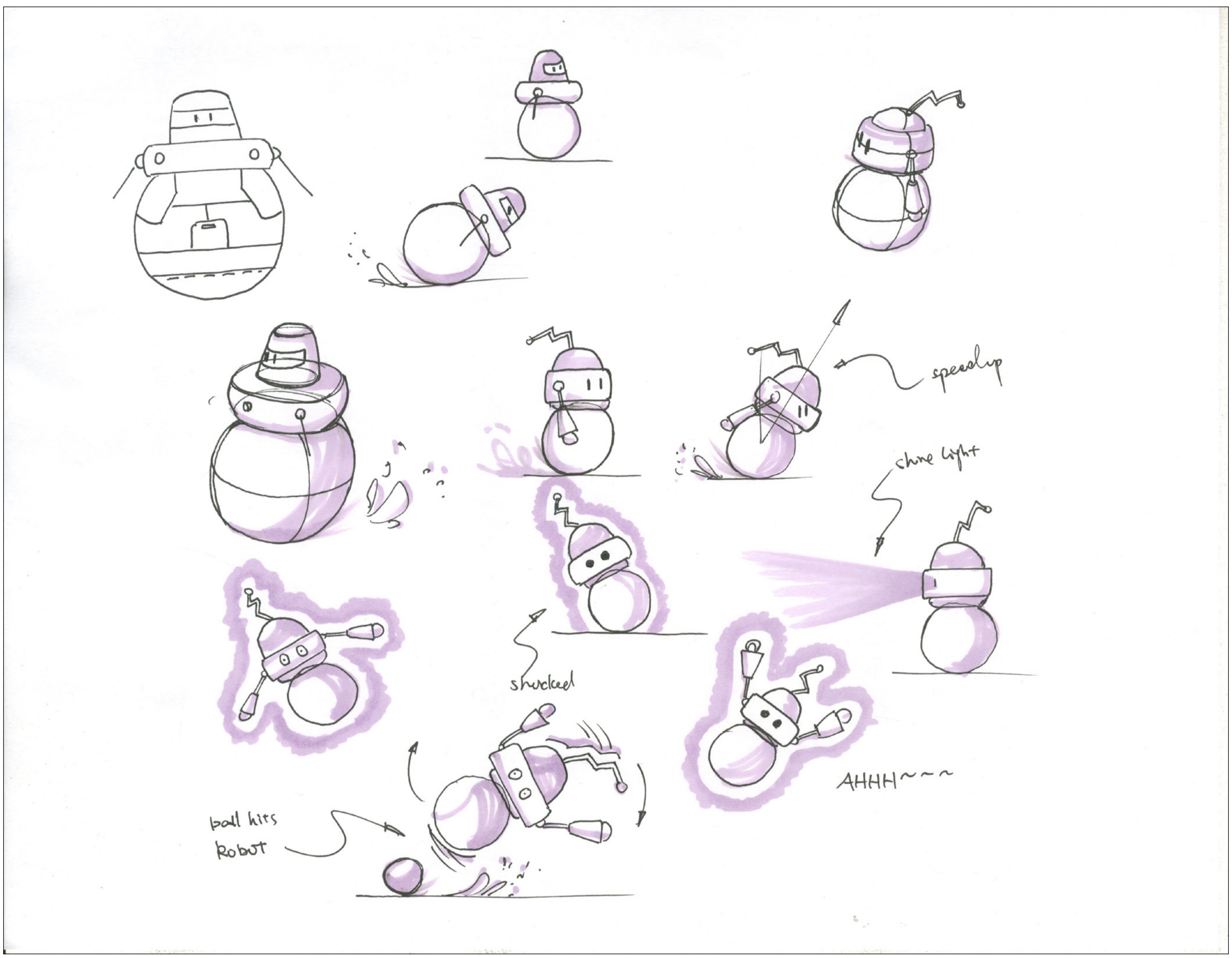

FIGURE 16. The robot design and its interactions were refined to give it a more humanistic character.

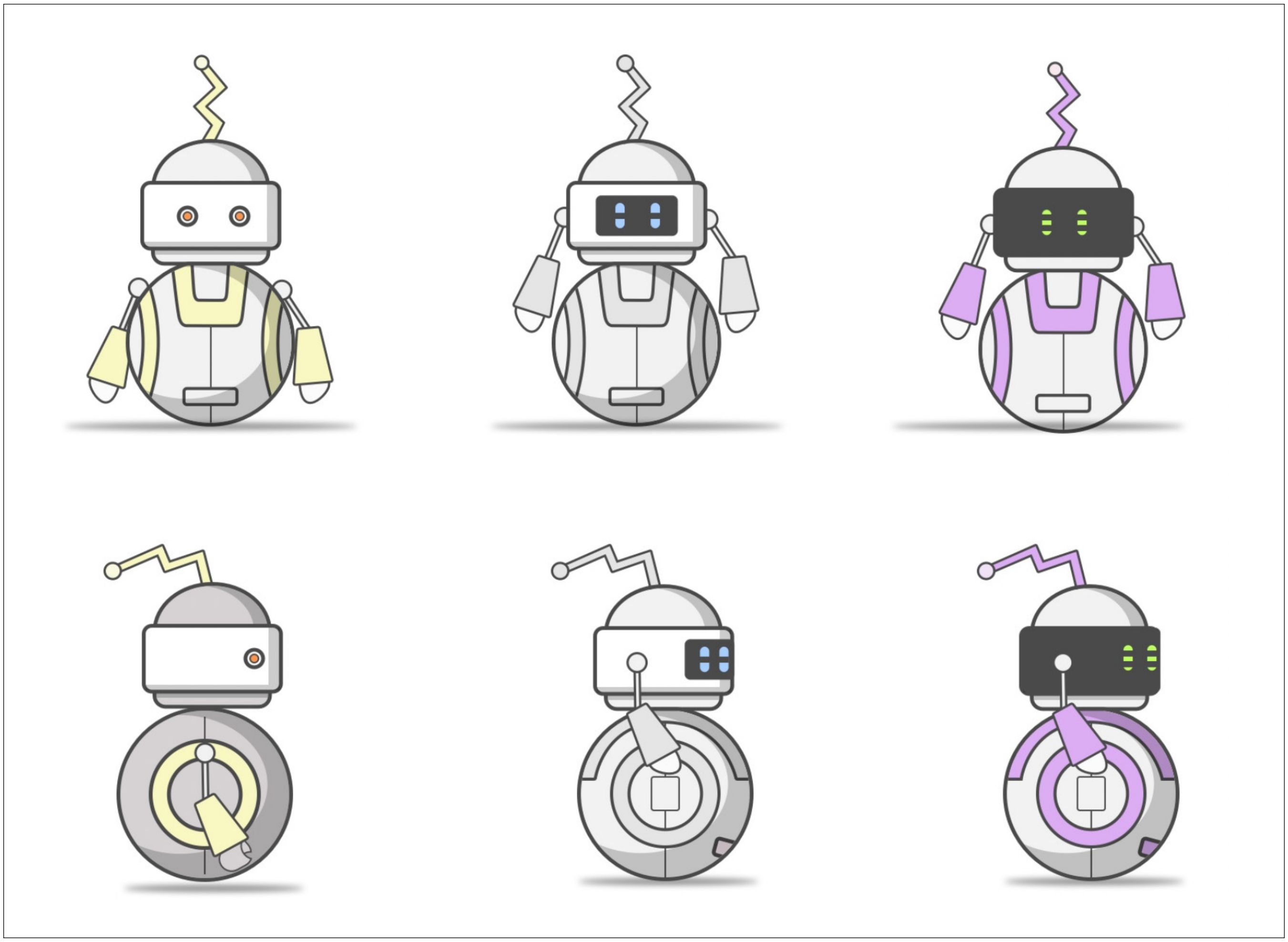

FIGURE 17. Options for customization to the final robot design were added later.

INTERDISCIPLINARY COLLABORATION

Designing an educational game such as *Particle in a Box* can only be successful through the collaboration of a multi-disciplinary team. Our team brought together people with expertise from a wide range of disciplines. Scientists and engineers helped ensure the fidelity of the game to quantum mechanics theory. Scholars of education helped align game mechanics to learning strategies. Game and visual designers together created a compelling game environment with engaging game mechanics. Given the development of the game in an academic setting, students also took part in design based on their individual interests and career goals. The design and evaluation of the game was itself a learning experience for a dynamic team. We highlight three strategies that proved particularly useful for our team.

The first strategy was the stability of a core team of designers and programmers to ensure continuity. The core team focused on the long-term design and development of the game and consists of faculty members and Ph.D. students. Several students (usually at the masters and undergraduate level) have joined, contributed, and graduated from the group so far, but the core group has remained the same. This stability has allowed us to build and learn from our past iterations instead of starting afresh each time.

The second strategy was to use ongoing evaluation of the game as a way to draw in students and help them find and define how they wanted to contribute to the game. Given the abstract nature of quantum mechanics, we found that many new students were initially hesitant about whether and how they could contribute. Asking them to participate as the end-users of the game for its evaluation allowed them to see how their limited knowledge of quantum mechanics was actually valuable to the design given its aim of reaching students with a similar knowledge-base. New team members drew on their observations as participants in the evaluation to find their interests in contributing to the game, which ranged from quick fixes such as changing the design of the background images to more substantial ones such as redesigning the game mechanics, designing sound-effects, or refining the evaluation protocols.

Our third strategy for fostering effective collaboration was the creation of a series of concept maps that served as

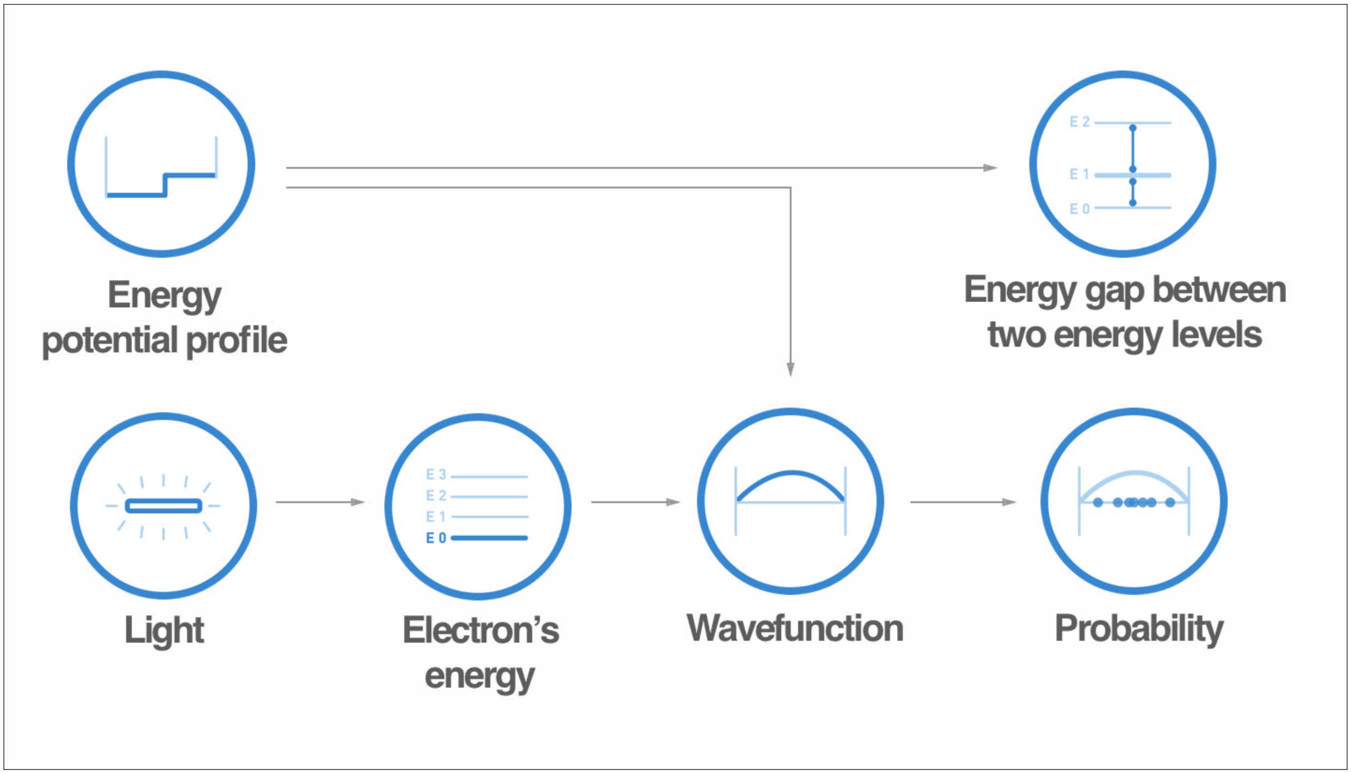

FIGURE 18. This concept map highlights the key concepts of quantum mechanics and their relationships.

blueprints for quantum mechanics concepts included in the game. These concept maps served as boundary objects (Leigh Star, 2010) by capturing the key features of the design while also fostering conversation about possibilities that could be explored. Figure 18 exemplifies one such concept map which highlights the key concepts of quantum mechanics and their relationships. It helps reduce the complex system down to smaller, communicable parts. These parts also constitute the main learning objectives for the game as described in Anupam et al. (2018). The concept maps have proven instrumental in anchoring the key objectives of the project while allowing for diverse game mechanics and storylines to emerge.

Together, these three strategies have proven effective for ensuring continuity and coherence of a design process that supports a dynamic and always-changing team while at the same time allowing for open-ended exploration and creative engagement that is central to the ethos of this collaborative design project.

FUTURE WORK

Building on our current work, we are developing a new prototype that engages students with the social nature of scientific practice. In this regard, we aim to integrate two additional characteristics into the game: a collaborative mode and a narrative.

Science is contingent on the cooperation of multiple researchers for the development and evaluation of scientific models (Kuhn, 1970; Longino, 1990; Harding, 1992). The new prototype will feature a collaborative mode where students can play the game together on the same device. This will encourage students to discuss, iterate on, and refine their understandings of concepts as they learn together. When designed well, cooperative learning activities can be more effective than individualistic and competitive alternatives (Johnson & Johnson, 2009) by supporting student's ability to work in teams and fostering inclusive learning environments (Slavin, 1990).

Scientific research is a social enterprise, marked by social and cultural values (Haraway, 1988; Longino, 1990; Harding, 1992; Barad, 2007). However, science and engineering students often study science devoid of the historic, social, political, and cultural environments of its development. A narrative has the potential to offer students an opportunity to reflect on the social nature of scientific research. In conjunction with a collaborative mode, it can contextualize the game world, bridge the different sections of the game, and move the game towards a more explorative and cooperative mode that is representative of scientific inquiry. We aim to develop a narrative that integrates the learning of concepts with a knowledge of how they were developed and how they can be used to foster a holistic understanding of classical and quantum mechanics.

Particle in a Box enabled us to examine the role of games in helping students learn complex scientific concepts such as those of quantum mechanics. Yet, given the rise of scientific misinformation on important issues such as anthropogenic climate change (Van der Linder, 2017) and vaccination (Stack, 2019), it is important to equip students with not just the knowledge of scientific concepts, but also the methods of scientific inquiry. Grounded in the work of feminist science and STS scholars, we aim to develop a suite of games, simulations, and interactive visualizations that move audiences beyond positivistic notions of science to a more critical and reflective understanding of scientific practice.

CONCLUSION

In this paper, we presented the design process of a digital game, *Particle in a Box*, aimed at supplementing curricula on quantum mechanics. Through a detailed description of our design process, this case complements general educational game guidelines that often overlook the details of design choices and rationales key to the success of science games.

We anchored our process on three design challenges: helping students draw upon and break free of their prior conceptions; creating learning environments that are scientifically accurate while also playful; and developing characters that are relatable but also resist gender stereotypes. Each challenge stems from foundational concepts of learning, science, and games: new learning is always built upon prior understandings; science is experimental and iterative; and it is important for both science and game cultures to be inclusive and cultivate diversity. Consequently, the consideration of these challenges is integral to designing effective and responsible science games no matter what the subject matter. For example, a game to support the learning of photosynthesis would benefit from both drawing upon and challenging students' preconceptions about plants, often rooted in Aristotelian concepts (Wandersee, 1986). By identifying these challenges and outlining our approach to address them, we aim for this paper to be a valuable design case in expanding and refining the understanding of the place and function of games in science education.

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