A Novel Interactive Paradigm for Teaching Quantum Mechanics

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Abstract: Quantum Mechanics (QM) is the foundation for science and engineering disciplines as diverse as physics, materials science, chemistry, and nanotechnology. However, educators face major challenges in teaching QM concepts to students given the abstract and non-experiential nature of QM. To address the above challenges we are creating and evaluating a virtual environment governed by the laws of quantum mechanics as a way to engage alternative ways of teaching and learning QM.

In our current prototype, students begin in a classical world that is governed by laws found in our everyday experiences. Here, they encounter potential and kinetic energies, the conservation of energy, the predictability of position, and the continuous nature of energies allowed. They later move into a nanoscale environment in which energies are quantized, electrons can tunnel through potential barriers, and only probabilities are known. The juxtaposition of these two worlds enables students to compare classical and quantum mechanics.

Introduction

Quantum Mechanics (QM) is the foundation of diverse science and engineering disciplines such as semiconductor physics, materials science, and nanotechnology. However, people almost unanimously agree that QM is extremely challenging to learn—especially for newcomers into the field. Students may spend several classes learning mathematical formulas that represent the behavior of particles in the QM world, but they may not form a clear intuitive understanding of these concepts. This is because, unlike classical mechanics, we do not have a first hand experience of QM phenomena. In fact, the laws of QM completely contradict our everyday experiences. As the famed physicist von Neumann declared, the only way to grasp the abstract concepts of QM is to “get used to them”.

Learning QM is very different from learning classical physics. In classical mechanics, students are able to make connections between the formulas they learn in class and the real-world phenomena they experience in their everyday lives. QM, on the other hand, directly contradicts students’ experiences in the real world and has no real world correlations. The only way to master QM concepts and become comfortable with them is to work in this area long enough to become accustomed to the counterintuitive behaviors of particles at the atomistic scales.

Can we foster experience-based learning of QM through interactive games and if so how? Can games be used along with a classroom environment to teach both theoretical and experiential aspects of QM? Research has confirmed the power of games as learning environments (Squire, 2011; Gee, 2007; Prensky, 2003) while cognitive science and other contemporary learning theories all highlight the importance of creating experiential and active learning opportunities to enhance students engagement and retention.

Over the past two years, our team consisting of faculty, graduate students, and undergraduate students from various disciplines such as Computer Science, Digital Media, Electrical Engineering, Human Computer Interaction, and Physics have collaborated to work on the design, development and evaluation of a game prototype. In this paper we outline the design and evaluation of an educational video game, Particle-in-a-Box, with the aim of providing students with a unique learning environment to facilitate experiential understanding of QM concepts. We describe the design of the game and discuss ongoing research methodologies for evaluating the effectiveness of the game both inside and outside of classroom.

Background

There have been several studies, which explore the effectiveness of games as teaching tools. Games constitute rich virtual worlds, which can provide multiple contexts for learners to understand abstract concepts of theoretical subjects and provide connections between these abstract ideas and their applications (Shaffer, 2005). Complex tasks can be presented as small core experiences in these game worlds, which can later be extended into longer, more complex sequences. This makes it easier to break down complex concepts and gradually increase their complexity through concurrent chaining (Mayo, 2009). Theory and practical knowledge should provide feedback to each other continually and as such, games and simulations help achieve the goal of reconciling theory, research and practice (Rieber, 1996).

As a starting point, we studied existing video games and visualizations in and outside the field of QM to see whether and how they address the problems noted above. Several games exist which explore aspects of QM such as *Quantum Tic-Tac-Toe* and *Quantum Minigolf* (Goff, 2006; Reinhard, 2007). These games have been designed to show a single quantum phenomenon (superposition and propagation respectively). Moreover, these games are designed on topics of QM that do not directly pertain to the basic concepts in undergraduate quantum physics. *Quantum Minecraft (qCraft)* is a game mod that intends to introduce the concepts of QM through the world of *Minecraft*, a popular game that evokes creativity by breaking and placing blocks. However, the QM concepts introduced in *qCraft* are the ones that are often referred to in science fiction (e.g. quantum entanglement and teleportation) and are not relevant to STEM education except the narrow area of quantum computing (Google, 2013). We also looked at a series of visualizations, called *Visual Quantum Mechanics*. This is a collection of Mathematica-generated online videos that show QM phenomena. These visualizations, however, are more similar to common simulation tools used by experts and may not be quite effective in engaging newcomers in the field as they are mathematically complex and do not utilize real-world metaphors.

Methodology

Game Design

We designed the game to focus on the particle-in-a-box problem, also known as the Infinite Potential Well Problem. The particle-in-a-box problem is commonly used as a thought experiment to simplify some of the concepts of quantum mechanics such as the Schrödinger equation and for comparing concepts between classical and quantum mechanics. It is typically shown as a standing wave within a one-dimensional box with infinitely high walls, while in classical mechanics it is merely depicted as a physical ball inside the same box.

In our game, appropriately titled “Particle in a Box”, we portray both the classical and quantum modes in separate virtual worlds, grounding the elements in the classical world in common, and identifiable objects such as a bowling ball to represent the particle. In contrast, we use abstract shapes and representations in the quantum world -- a plasma sphere to represent the electron for example. These representations are chosen to show a sense of scale for the bowling ball and a sense of fantasy for the electron. We designed two very distinct environments that allow students to contrast the properties in classical physics with those of quantum mechanics.

Classical World

We designed a level, which follows laws of classical physics to provide a comparison point for the quantum levels succeeding it. The player guides a small avatar, nicknamed “The Dude”, by using the arrow keys along a linear path in a 2D perspective. The overarching goal for each level is to collect all of the collectibles in the level and bring them to a portal while avoiding a moving obstacle in the path. The obstacle in the classical world is a bowling ball, and it can reach certain areas of the stage only when it reaches certain amounts of energy. The collectibles are represented by heavy weights, which were chosen because the physical qualities of weights can represent energy and the weights can have variations in length, which correspond to an increase in the player’s probability of getting hit. We wanted a way for the player to manipulate the energy of the particle in the classical and QM worlds, and picked a common video game mechanic of item collection to make it easy to understand. The act of picking up a collectible increases the total energy of the bowling ball, making it move faster and making The Dude more susceptible to getting hit by the ball.

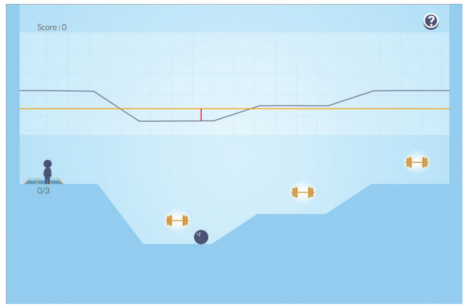

Figure 1: Classical mechanics level depicting placement of energy graphs.

Several design consideration went into the placement decisions for the energy graphs depicting the potential, kinetic, and total energy of the bowling ball. In early game mockups, we showed these energy graphs in a separate popup window, but later found it to be too obtrusive and not immediately relatable to the ball's movement. We soon incorporated the graphs into the world itself, having it span the length of the stage to match up with the ups and downs of the stage itself. During initial pilot tests, we observed that participants incorrectly assumed that The Dude could interact with the graphs because of the visual qualities of the graphs. Finally, we settled on making the graphs visually distinct from the game but still stretch the full length of the screen for clarity (see Figure 1).

Quantum World

The design of the Quantum world mirrors that of the classical world, but with key differences to highlight the contrast between the two worlds. The visual design transitions to a darker color scheme with a fantasy mood to indicate its departure from everyday reality. The obstacle is now a plasma sphere representing an electron, whose position is unknown to the game player until a 'measurement' is made. Depending on the energy state of the electron, the probability of the electron appearing anywhere on the flat, one-dimensional stage will vary. Every few seconds a measurement is taken, revealing the position that the electron takes on during that particular moment in time. This makes the gameplay unpredictable and random. The collectibles are now colored lights instead of weights, representing packets of visible light photons (see Figure 2).

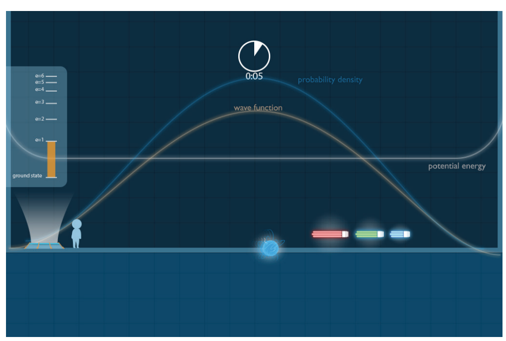

Figure 2: Mockup of quantum level with probability density graph and separated energy states.

This world has undergone several iterations as well. The electron originally stayed persistent until the next measurement was taken, but this was revealed to change the players' strategy as well as reflecting inaccurate principles. Now we have the particle disappearing immediately after it is revealed, increasing the sense of uncertainty. We also once included a probability density curve in the background in addition to the wave function, but this felt redundant, as the curve will be proportional to the amplitude of the wavefunction squared. Instead, we plan to represent the probability as a density heatmap on the floor of the game (see Figure 3).

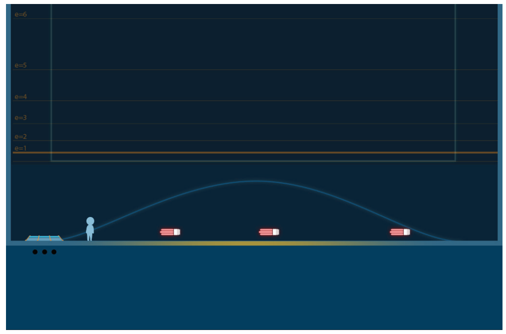

Figure 3: New Quantum level with integrated energy graphs and probability heat map.

Introducing Charges

After conducting our pilot study, we designed an additional level to show variations in potential energy profiles for the QM stage. We wanted to explain how a particle's potential profile could be affected by charges. The game mechanics for this portion resembles a puzzle game where the user could drag positive and negative charges along a path to see how this affects the potential profile. The background of the stage shows a "target" potential energy that the player will aim to reach with the true potential by manipulating both position and magnitude of the positive and negative charges. Once the potential graph matches the target potential, the stage is unlocked and the player moves the Dude as they would with a regular QM level (see Figure 4).

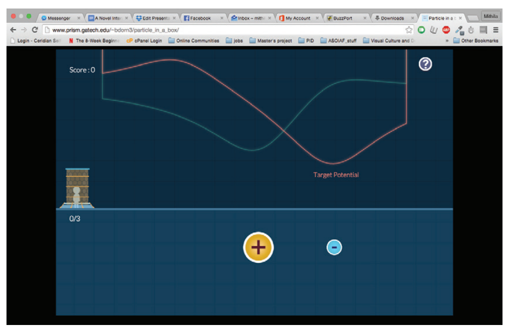

Figure 4: The Charges puzzle to match the target potential profile

Tutorial

Given the abstract nature of concepts and the educational aims of the game, we decided to include a set of tutorials to accompany the different levels of the game. We needed two kinds of tutorials, one for explaining the actual concepts of classical and quantum mechanics and the other to explain game controls. For the purpose of the educational aspect of the game, we focused on the scientific concepts tutorials in our designs. These tutorials went through several iterations as we worked to find the best way to incorporate the information seamlessly into the game without overwhelming the user or not presenting enough information to the user. In our very first set of pilot tests, the tutorials began as a series of presentation slides shown separately from the game itself; this helped us to assess the level of detail the tutorials should get into before implementing them within the game. As we progressed we moved on to still images incorporated within the game right before each level, explaining the physical phenomenon that would be demonstrated in the following level. In the next iteration we added animations to the tutorials to present information more dynamically and give a preview of the mechanics present within the level (see Figure 5).

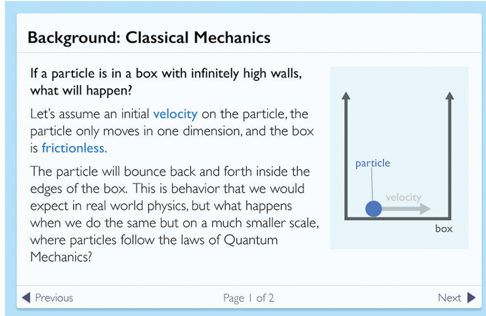

Figure 5: Tutorial page for Classical mechanics level.

Evaluation

For evaluating the game, we initially conducted a pilot study, to help us understand any issues with gameplay and to enhance the evaluation process. We are now conducting a series of in-class studies with undergraduate students of quantum mechanics who were our target users.

Pilot Study

We devised the pilot study to evaluate an early version of 'Particle in a Box' for improvements to the educational aspect as well as gameplay. The primary aim of this was to provide an initial probe into the effectiveness of the game in students' understanding of the basic concepts of Quantum Mechanics. We did this by testing the effectiveness of the visual representation of the Classical and the Quantum environments and evaluating students' understanding of the contrast between these two worlds and their underlying rules.

We conducted these pilot studies on 10 participants. Since these tests were conducted to help us enhance the design, the participants from this study had no formal training in the concepts of Quantum Mechanics. The research methodology for the pilot studies consisted of four distinct phases: pretest, gameplay, posttest, and semi-structured interview. We began by administering a pretest on the participants, consisting of some multiple-choice questions and some one-line answers about the basic concepts of quantum mechanics. The purpose of this pretest was to determine the level of initial knowledge the participants had about these concepts and to provide a baseline to measure their posttest results. After the pretest, we let the participants play through the game, consisting of a Classical Mechanics tutorial and level followed by a Quantum Mechanics tutorial and level. While the participants were playing through the game, we observed them and took notes on their progress and pain points. Afterwards, we administered a posttest consisting of all the questions from the pretest as well as some questions about the game mechanics and usability heuristics of the game. Finally, we conducted semi-structured interviews with the participants to determine what they liked, where they faced problems, which concepts they understood, which concepts they did not understand, and any suggestions they may have had.

Our results were positive: we found that while all the participants answered the questions about Classical Mechanics correctly, students also showed some improvement in their understanding of QM concepts presented in the game. For example, students were asked: "In Quantum Mechanics, if you had a particle inside of a 1-dimensional box, where would be the highest probability of finding it, assuming the particle is in the lowest energy level?" Three out of 10 participants were able to give the correct answer before the game; while 5 out of 10 participants were able to give the correct answer after the game. Furthermore, more students chose to answer questions about QM in the posttest as opposed to selecting 'I don't know' as an option in the pretest.

When asked to describe the goal of the game, most participants correctly explained how it would help them compare and contrast Classical and Quantum Mechanics. One participant wrote a succinct response saying "the goal is to teach the player the difference between classical and quantum mechanics. I think the game does a good job describing the difference between the two genres of physics." Students were able to understand the unpredictable nature of QM. "I don't know how to predict the position of the particle in the quantum mechanics section", "what I found most difficult was the unpredictability of where the particle will be", were some of the comments about that level. Their comments reflect the difficulties associated with the probabilistic nature of Quantum mechanics itself.

Based on the analysis of the pilot tests, we concluded that the gameplay was easily understood but the tutorial for the quantum mechanics concepts needed to be concise and precisely worded. We used the qualitative results from the posttest questionnaire to determine areas of improvement for the future of the game. Meanwhile, we also added new levels to incorporate the concept of charges so that the participants could understand how these charges affect the potential profile.

In-class Study

We are currently conducting a series of in-class studies with undergraduate students studying quantum mechanics--our target audience for the game. As of now, we have evaluated 5 participants who were recruited through a Physics class at Georgia Tech teaching basic concepts of quantum mechanics. The 5 participants were evaluated at the same time and the study was structured into four parts: pretest, gameplay, posttest, and a focus group discussion.

The pretest and the posttest for this set of evaluations have been adapted for the participants. These tests consist of more direct and focused questions as appropriate for the participants who are already familiar with QM. The questions are designed to measure their inherent understanding of QM rather than gauge how well they can solve equations. The focus group includes discussions about what the participants like and dislike or what was confusing about the game, and also suggestions about how the game could be improved.

Future Work

We have developed a playable version of the game, which includes the basic introductions to the two environments of classical mechanics and of quantum mechanics. In the future, we will increase the number of levels with increasing difficulty in the game to include more concepts of Quantum Mechanics. For designing these levels, we have tried to incorporate the structure of basic QM courses. For example, the next level will also include the concept of charges and how these positive and negative charges affect the potential energy profile and the wave function. We will include a ‘level lock’ where the player cannot move forward unless the potential profile of the wave matches the desired profile. The player can manipulate the potential profile using the position and magnitude of the charges.

Our next goals are to increase the complexity of the quantum levels and simultaneously introduce more scientific concepts about quantum mechanics, while maintaining the scientific accuracy of the QM concepts. We also want to devise an overarching narrative to make the gameplay more compelling so players will be able to follow the progress of their onscreen avatar The Dude and understand the motivations behind his actions. Finally, we also want to make the tutorial fully interactive. While completing these goals, we plan on conducting further in-class studies to continue evaluating of Particle in a Box to ensure its effectiveness in teaching Quantum Mechanics.

Conclusion

We acknowledge that it is challenging for students to learn Quantum Mechanics if they are new to this field. To address this challenge, we have designed, developed, and evaluated a game as a novel approach to teaching QM to beginners by visualizing formal abstract concepts in interactive worlds. We chose a low-level QM concept (Particle in a Box) to base our game on, and incorporated established game mechanics that are relatively easy to pick up. The game is in the form of two virtual environments: one governed by classical mechanics and one governed by the laws of quantum mechanics to help students compare and contrast the two worlds so that they can learn Quantum Mechanics through experience and gameplay along with classical classroom methods.

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