Beyond Motivation and Memorization: Fostering Scientific Inquiry with Games

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Abstract
Given the rise of scientific misinformation, there is a critical need for students to learn the practices of scientific inquiry along with scientific concepts. In this work-in-progress paper, we posit that digital games are conducive to learning both as they enable collaborative virtual scientific experimentation and modeling. We put forward design guidelines for games that facilitate such learning. We then illustrate one instance of employing these guidelines in the design of *Psi and Delta*, a collaborative science game to help students learn the basic concepts of quantum mechanics through inquiry.

Author Keywords
Game Design; Serious Games; Feminist Science; Quantum Mechanics; Inquiry; Collaborative Learning

CSS Concepts
• Applied computing~Interactive learning environments
• Applied computing~Collaborative learning

Introduction
Rising scientific misinformation on pressing societal issues such as anthropogenic climate change [28] and vaccines [38] highlights an urgent need for citizens to understand the practices of scientific inquiry along with scientific concepts. Knowing both empowers citizens to better evaluate new scientific developments and participate in discussions surrounding scientific research and science policy. Consequently, in 2012, the

National Research Council (NRC) proposed a shift in science education away from imparting ready-made concepts towards engaging students with the practices of scientific inquiry and fostering a deeper understanding of scientific knowledge [32].

Games are conducive to learning both scientific concepts and inquiry as they afford the creation of virtual worlds where students can conduct virtual experiments and build scientific models together [4,13,31,37]. However, research into the design and capability of games to foster scientific inquiry is limited. Studies generally focus on developing and evaluating games that improve students' motivation and ability to memorize scientific concepts. Given the necessity of engaging students with scientific inquiry, there is a need for the development and testing of games and game design guidelines addressing this gap.

The objective of this work-in-progress paper is twofold. First, building on recent literature in science, education, and games, we propose guidelines for designing games that engage students with the practices of scientific inquiry. Second, we illustrate how those guidelines inform the design of *Psi and Delta*, a digital game that supports undergraduate students' learning of quantum mechanics (QM). QM is difficult to learn and teach as it is counterintuitive and cannot be directly experienced [20,30,34]. Yet, these attributes also make QM conducive to learning scientific inquiry as they provide a rich space for the development of hypotheses grounded in ideas about both the nature of the world and how we justify our knowledge of it. For example, Heisenberg's uncertainty principle states that one cannot accurately measure both the position and momentum of a particle together as measuring one introduces errors in the other. Einstein, who believed in a deterministic universe, argued that this problem is epistemological and is caused by our ignorance of how to measure accurately. Bohr, however, argued that the uncertainty is ontological and inherent to the nature of the universe. The possibility of such discussions makes QM suitable for cultivating "strong reflexivity," encouraging students to reflect on the entanglement of scientific problems with one's underlying beliefs about the world [16]. Games can support the development of strong reflexivity and scientific inquiry for QM by allowing virtual experimentation on otherwise inaccessible QM phenomena. *Psi and Delta* aims to provide such an opportunity as it builds on the success of its predecessor *Particle in a Box* which immerses students in a virtual QM world where they experientially learn probability, a core QM concept [1,2].

Background

While educational games can be a source of motivation [6,9,10], their effectiveness on learning is unclear. Some studies suggest that games can support learning [9], while others argue that more evidence is needed [6,10,29]. Establishing consensus is difficult as the effects of factors such as game details, subject-matter, students, and context cannot be easily isolated. Consequently, guidelines for designing educational games are usually broad [23,24,27]. For example, Klopfer et al. [23] developed a set of 22 overarching principles, suggesting that educational games should have clear goals, authentic problems, and foster inquiry. While such guidelines are widely applicable, they need to be supplemented by more specific recommendations that accommodate scientific inquiry.

Games that successfully engage students with scientific inquiry offer more specific design insights [3,4,11,21,24]. For example, in *EcoMUVE* [21,24],

Table 1. Summary of Design Guidelines

Designing Situations that Foster Inquiry
In-game situations should have the following qualities:

- Uncertain Problems
- High Degree of Freedom

Structuring Collaboration
Collaborative activities should be designed based on:

- Positive Interdependence
- Individual Accountability
- Minimal Collective Cognitive Load:
  - Smaller Team Sizes
  - Clearer Roles
  - Adequate Complexity
  - Sufficient Guidance

Meaningfully Integrating Play and Learning
Play and learning can support one another when the game:

- Incorporates Scientific Visualizations
- Maps all concepts on to game mechanics

players explore a small village where the local fishes are dying. Adopting the role of virtual ecosystem scientists, players develop research questions and hypotheses pertaining to the decline of the fishes, test evidence from the ponds using virtual scientific apparatus, and collaborate to propose an appropriate solution to the instructor of their class. Of particular note are the grounding of inquiry in a concrete situation (dead fishes), provision of clear roles for students (ecosystem scientists) and design of immersive environments with a high degree of freedom (availability of several scientific apparatus and sources of evidence). Together, these characteristics encourage students to engage collaboratively in scientific inquiry.

Design Guidelines

Our approach to developing design guidelines for science games was rooted in pragmatism and feminist philosophy of science. Central to our approach is the idea that students should learn science by *doing* science like scientists do in a social environment. Scientific inquiry begins with a movement of concrete situations from certainty to uncertainty [12]. For example, Bohr's hypothesis that a change in the experimental apparatus changes the behavior of the electron moved a foundational principle of classical mechanics to uncertainty – the separation of the observer and observed. Subsequently, scientists develop specific problems, and test hypotheses. This pattern of scientific inquiry provided the foundation for our guidelines. It is also important to highlight that scientific inquiry is inseparable from the social, political, cultural situation within which it operates. Significant advancements in QM were made possible in the 1920s due to the intermediary peace between the two world wars. Conversely, this research was instrumental in the development of nuclear weapons. A detailed analysis of how games should be designed to incorporate the situated nature of science is beyond the scope of this paper and needs further research. Our final guidelines were supplemented by a review of literature in science, learning, and game studies pertaining to scientific inquiry and collaboration. Based on this analysis, we propose the following guidelines.

Designing Situations that Foster Scientific Inquiry
The NRC [32] proposed eight practices of scientific inquiry that students should engage with (Table 2). These practices are highly interconnected. For example, the choice of a scientific model affects data collection and analysis of data can affect the model [8]. Artificially separating these practices can therefore misrepresent scientific inquiry [5,25]. We suggest that educators not isolate these practices, but design situations that foster the pattern of inquiry as a whole. We posit such situations have the following qualities:

- Uncertain Problems: inquiry begins with a movement from certainty to uncertainty [12]. Games can facilitate this movement by requiring students to develop the uncertainty of game situations themselves and not describing it for them. This engages students in defining and resolving problems.
- High degree of freedom: the pursuit of inquiry requires students to have adequate room to develop and test their hypotheses [24]. A high degree of freedom can also reduce ad-hoc trial-and-error by making it practically infeasible.

Structuring Collaboration
Collaboration is not only integral to scientific inquiry, it is also an effective educational strategy. Several studies have affirmed the positive impact of collaboration on educational outcomes [19,33,35] and

Table 2. Scientific Practices Outlined by the National Research Council

In 2012, after building on two decades of educational research, the National Research Council outlined eight key scientific practices that students should engage in [35]:

- Asking questions
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Constructing explanations
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

its advantages over individualistic and competitive alternatives [18,19]. However, unstructured collaboration can be detrimental to learning. Some students may "free-ride" on the abilities of others and not contribute [26]. In other cases, collaboration can lead to 'group think,' a phenomenon where participants pursue less feasible courses of action if they are unanimous, instead of evaluating alternative, more appropriate actions [17]. Consequently, success in the game should be contingent on developing appropriate collaborative solutions to in-game problems [39]. Slavin [36] suggests two guidelines to achieve this:

- Positive Interdependence: there must be a common goal that requires all members to work together.
- Individual Accountability: the group's success must depend on the individual learning of all members.

To support effective communication and coordination, Kirschner et al. [22] suggest that collaborative activities must aim to minimize the collective cognitive load of a group. This entails having:

- Small teams, to improve communication
- Clear team roles, to prevent confusion
- Adequate task complexity that warrants collaboration
- Sufficient task guidance for new situations

Meaningfully Integrating Play and Learning

Games should be designed such that play and learning meaningfully support each other. This implies that learning new concepts should aid the player in their game actions, and performing actions should refine their understanding of concepts [1,39]. Without this integration, games may not support learning or fail to be engaging [7]. Borrowing from the design process of our previous game, *Particle in a Box* [1], we propose that games should:

- Incorporate scientific visualizations: this supports students' understanding of their application.
- Map concepts to game mechanics: this ensures that all concepts can be experimented and engaged with.

Psi and Delta

In this section, we describe *Psi and Delta*, a game that helps students collaboratively learn basic QM, and discuss how its design was informed by our guidelines.

In *Psi and Delta*, students adopt the role of two robots, with the aim of defeating an opposing robot in a world governed by the laws of QM. Students accomplish this task by using QM concepts to lure and "shock" the opposing bot. If a student's bot touches the opposing bot or gets "shocked", it loses part of its health. If any player's bot loses all their health, the level restarts.

The game is divided into two parts. In part 1, students develop models of the concepts of superposition and probability. According to QM, when an electron is confined in a small area, it will enter a superposition, i.e., it will exist in multiple positions simultaneously. To

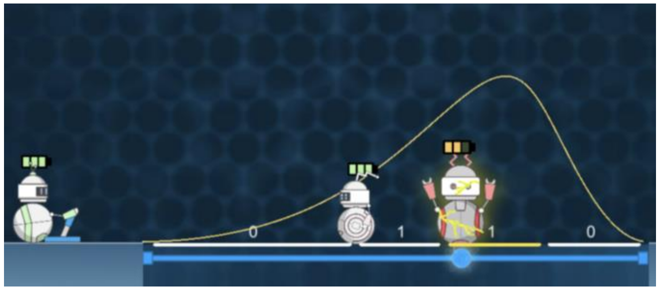

Figure 1: A player pulls the lever (left), which collapses the electron (blue dot), and shocks the opposing bot on the platform.

break this superposition, one needs to take a "measurement." In the game, the electron is confined in a small blue quantum wire. Students can pull a lever to "measure" the electron, which collapses it to an unpredictable position on the wire for a brief moment (see Fig. 1). Any robot standing on a platform directly above the collapsed electron will get "shocked" and lose some health. The position where the electron collapses is probabilistic, i.e., some positions are more likely than others. The relative probability of these positions is illustrated by the electron's probability density function (PDF), the orange curve in Fig. 1. The longer the platform and the higher the curve above it, the more likely the electron will be measured under it. After each measurement, the electron returns to superposition.

In part 2, students develop models of energy levels. Here, the opposing bot has a shield which protects it from getting shocked. To break the shield, the electron needs more energy. Electrons can only have a discrete amount of energy such as 1 eV (electron-volt) or 3 eV in the case shown in Fig. 2, but nothing in between. Energy can be supplied to an electron in the form of light, which consists of discrete energy packets (photons) whose energy depends on their color. To excite an electron from a lower energy (say 1 eV) to a higher energy (3 eV), one must shine photons with the exact energy as the gap (2 eV). In the game, students can shine light using a lamp and also change its color.

Designing Situations that Foster Inquiry

In the early levels, the game guides learners through basic QM concepts using signboards, pacing complexity gradually [40]. Subsequently, students face unguided situations which feature new concepts that build on the basic concepts. For example, after learning how to operate the lamp light, students face a situation where

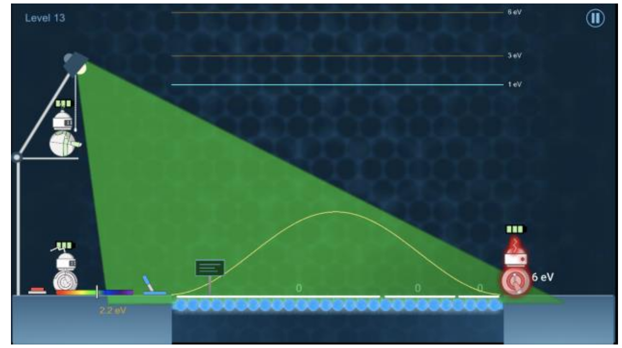

Figure 2: A player pulls the lamp switch (above) and shines green light to change the electron's energy.

they need to understand how to an increase the electron's energy without guidance. Students initially attempt to shine the default colored light and notice no change. This spurs a discussion that brings out their assumptions about the nature of matter. For example, students often draw on their daily experiences and assume that if an object does not react when given energy, then more energy is needed (such as pushing a heavy boulder harder). Based on this assumption, they attempt to increase the energy of the lamp light to its maximum value and shine light again. However, this experiment too produces no change and makes the situation more uncertain. Does light need to be shined multiple times to increase the electron's energy? What color of the light will be absorbed by the electron? Ad-hoc trial and error is arduous as there is a high degree of freedom with several possible energies provided by the lamp. Shining light requires careful coordination between the students and can be difficult to execute quickly. By not describing the problem situation and making it difficult to proceed by ad-hoc trial-and-error the game encourages students to reflect on their beliefs and on how those beliefs shaped their experiments.

Through inquiry and with support from an energy diagram (figure 2, top), students gradually develop the notion that matter can possess discrete levels of energy in which case it will only absorb light of specific colors.

Structuring Collaboration

Success in *Psi and Delta* requires students to strategize and coordinate actions to defeat the opposing bot. This promotes positive interdependence and individual accountability. For example, in part 1, player one (P1) can stay at the lever and take measurements, while P2 lures the opposing bot onto a platform. When ready, P1 takes measurements that can shock the opposing bot while P2 jumps and redirects the opposing bot. To succeed, both students need to consider factors such as the shape of the curve, length of the platforms, distance of the opposing bot, and bot health. This evokes a rich discussion where students share and refine hypotheses. Another example can be seen in part 2. To shock the shielded opposing bot, students need to increase the energy of the electron. To do this, they analyze the energy level diagram and calculate the color of light needed. Then, to change the lamp light's color, one bot stands on a button to activate a slider, while the other moves the slider across a spectrum of colors until it is on the color with the right energy. To shine light, one bot jumps on the other to reach an elevated platform on which the lamp is located and pulls the switch. It is not possible to succeed here individually or without a shared understanding of QM.

Meaningfully Integrating Play and Learning

We integrated standard QM visualizations found in common course books such as Griffiths [14] into the game environment. This helps students transfer their understanding of these concepts between the game and classes. For example, when the player bot approaches a platform, the area under the curve is displayed. This allows students to analyze the relative probabilities of measuring the electron under a platform and plan their strategy accordingly. In part 2, the visualization of the energy levels helps students see the possible energies of the electron. When students change the electron's energy, they observe a change in the orange PDF curve, which requires them to adapt their strategies accordingly. The game therefore, draws attention to the dynamic relationships between concepts through play.

Conclusion and Future Work

In this work-in-progress paper, we developed three key design guidelines for digital games aimed at engaging students with the practices of scientific inquiry. We recommend that designers structure collaboration, focus on designing situations that foster inquiry as a whole instead of separating its practices, and meaningfully integrate play and learning. We employed these guidelines to describe the design of *Psi and Delta*, a collaborative game to help college and high school students learn introductory quantum mechanics.

Psi and Delta was selected for demonstration at the ACC Smithsonian Creativity Festival at the National Museum of American History which attracted over 30,000 visitors. Based on feedback at the festival and pilot tests, we are currently revising the game. Drawing on the research of feminist and science scholars [5,15,16], we aim to situate the game in a narrative that captures the communal and iterative nature of science and contextualizes the concepts in the history of their development. Together, the collaborative and storied nature of the environment can help engage students with not just scientific concepts and inquiry, but also the entanglement of science and society.

References

1. Aditya Anupam, Ridhima Gupta, Shubhangi Gupta, Zhendong Li, Nora Hong, Azad Naeemi, and Nassim Parvin. Forthcoming. Design Challenges for Science Games: The Case of a Quantum Mechanics Game. *International Journal of Designs for Learning*.

2. Aditya Anupam, Ridhima Gupta, Azad Naeemi, and Nassim JafariNaimi. 2018. Particle in a Box: An Experiential Environment for Learning Introductory Quantum Mechanics. *IEEE Transactions on Education* 61, 1: 29–37.

3. Anna Arici and Sasha Barab. 2013. Transformational Play; Using 3D Game- Based Narratives to Immerse Students in Literacy Learning. *European Conference on Games Based Learning*, 35–44.

4. Sasha A. Barab, Melissa Gresalfi, and Adam Ingram-Goble. 2010. Transformational Play: Using Games to Position Person, Content, and Context. *Educational Researcher* 39, 7: 525–536.

5. Karen Barad. 2007. *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Duke University Press.

6. Elizabeth A. Boyle, Thomas Hainey, Thomas M. Connolly, et al. 2016. An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games. *Computers & Education* 94: 178–192.

7. Amy Bruckman. 1999. Can Educational Be Fun?

8. Scott Buchanan. 1927. *Possibility*.

9. Douglas B. Clark, Emily E. Tanner-Smith, and Stephen S. Killingsworth. 2016. Digital Games, Design, and Learning: A Systematic Review and Meta-Analysis. *Review of Educational Research* 86, 1: 79–122.

10. Thomas M. Connolly, Elizabeth A. Boyle, Ewan MacArthur, Thomas Hainey, and James M. Boyle. 2012. A systematic literature review of empirical evidence on computer games and serious games. *Computers & Education* 59, 2: 661–686.

11. Chris Dede, Tina A Grotzer, Amy Kamarainen, and Shari Metcalf. 2017. EcoXPT: Designing for Deeper Learning through Experimentation in an Immersive Virtual Ecosystem. *Educational Technology & Society* 20, 4: 166–178.

12. John Dewey. 1938. *Logic The Theory Of Inquiry*.

13. James Paul Gee. 2005. Learning by Design: good video games as learning machines. *E-Learning* 2, 1: 5–16.

14. David J. Griffiths. 2005. *Introduction to Quantum Mechanics*. Pearson Education International.

15. Donna Haraway. 1988. Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective. *Feminist Studies* 14, 3: 575.

16. Sandra Harding. 1992. Rethinking standpoint epistemology: What is" strong objectivity?". *The Centennial Review* 36, 3: 437–470.

17. Nassim JafariNaimi and Eric M. Meyers. 2015. Collective Intelligence or Group Think?: Engaging Participation Patterns in *World without Oil*. *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing - CSCW '15*, ACM Press, 1872–1881.

18. David W. Johnson. 1981. Student-Student Interaction: The Neglected Variable in Education. *Educational Researcher* 10, 1: 5.

19. David W. Johnson and Roger T. Johnson. 2009. An Educational Psychology Success Story: Social Interdependence Theory and Cooperative Learning. *Educational Researcher* 38, 5: 365–379.

20. I. D. Johnston, K. Crawford, and P. R. Fletcher. 1998. Student difficulties in learning quantum mechanics. *International Journal of Science Education* 20, 4: 427–446.

21. Amy M. Kamarainen, Shari Metcalf, Tina Grotzer, and Chris Dede. 2015. Exploring Ecosystems from the Inside: How Immersive Multi-user Virtual Environments Can Support Development of Epistemologically Grounded Modeling Practices in Ecosystem Science Instruction. *Journal of Science Education and Technology* 24, 2–3: 148–167.

22. Paul A. Kirschner, John Sweller, Femke Kirschner, and Jimmy Zambrano R. 2018. From Cognitive Load Theory to Collaborative Cognitive Load Theory. *International Journal of Computer-Supported Collaborative Learning* 13, 2: 213–233.

23. Eric Klopfer, Jason Haas, Scot Osterweil, and Louisa Rosenheck. 2018. *Resonant Games: Design Principles for Learning Games that Connect Hearts, Minds, and the Everyday*. MIT Press.

24. Janet L. Kolodner, Tamer Said, Kenneth Wright, and Amy Pallant. 2017. Drawn into Science Through Authentic Virtual Practice. *Proceedings of the 2017 Conference on Interaction Design and Children - IDC '17*, ACM Press, 385–391.

25. Thomas S. Kuhn. 1970. *The structure of scientific revolutions*. University of Chicago Press, Chicago.

26. Marjan Laal, Loabat Geranpaye, and Mahrokh Daemi. 2013. Individual Accountability in Collaborative Learning. *Procedia - Social and Behavioral Sciences* 93: 286–289.

27. Petros Lameras, Sylvester Arnab, Ian Dunwell, Craig Stewart, Samantha Clarke, and Panagiotis Petridis. 2017. Essential features of serious games design in higher education: Linking learning attributes to game mechanics: Essential features of serious games design. *British Journal of Educational Technology* 48, 4: 972–994.

28. Sander van der Linden, Anthony Leiserowitz, Seth Rosenthal, and Edward Maibach. 2017. Inoculating the Public against Misinformation about Climate Change. *Global Challenges* 1, 2: 1600008.

29. Richard E. Mayer. 2019. Computer Games in Education. *Annual Review of Psychology* 70, 1: 531–549.

30. Rainer Müller and Hartmut Wiesner. 2002. Teaching quantum mechanics on an introductory level. *American Journal of Physics* 70, 3: 200–209.

31. National Research Council (U.S.). 2011. *Learning science through computer games and simulations*. National Academies Press, Washington, D.C.

32. National Research Council (U.S.). 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. National Academies Press, Washington, D.C.

33. Jeremy Roschelle. 1992. Learning by Collaborating: Convergent Conceptual Change. *The Journal of the Learning Sciences* 2, 3: 235–276.

34. Homeyra Sadaghiani and Lei Bao. 2006. Student Difficulties in Understanding Probability in Quantum

Mechanics. *AIP Conference Proceedings*, AIP, 61–64.

35. Robert E. Slavin. 1980. Cooperative Learning. *Review of Educational Research* 50, 2: 315–342.

36. Robert E. Slavin. 1990. Cooperative Learning and Student Achievement. *Educational Leadership* 47, 52–54.

37. Kurt Squire. 2011. *Video Games and Learning: Teaching and Participatory Culture in the Digital Age*. Teachers College Press.

38. Liam Stack. 2019. Measles Cases Reach Highest Level in More Than 25 Years, C.D.C. Says. *The New York Times*. Retrieved June 28, 2019 from https://www.nytimes.com/2019/05/30/health/measles-cases.html.

39. M. Villalta, I. Gajardo, M. Nussbaum, J.J. Andreu, A. Echeverría, and J.L. Plass. 2011. Design guidelines for Classroom Multiplayer Presential Games (CMPG). *Computers & Education* 57, 3: 2039–2053.

40. Monica Visani Scozzi, Ioanna Iacovides, and Conor Linehan. 2017. A Mixed Method Approach for Evaluating and Improving the Design of Learning in Puzzle Games. *Proceedings of the Annual Symposium on Computer-Human Interaction in Play - CHI PLAY '17*, ACM Press, 217–228.