Assignment 3: Teaching Quantum Computing with Virtual Reality

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***Abstract*—** Quantum Mechanics, the frontier of next generation computing, is as revolutionary as it is complex. From imaginary planes, to spooky behavior and probability solutions, teaching quantum mechanics requires a unique approach, study material, and hands-on practical exploration in order to provide a glimpse into the quantum world.

1 RESERCH LOG

1.1 Background

The first assignment focused on researching the field of teaching Quantum Mechanics and Quantum Computing. It is evident form the research that there is considerable need for educating non-scientific students, as well as professionals which may work with the technology, without delving too deep into its inner workings. No formal study curriculum exists as teachers attempt to recycle classical physics teaching techniques or attempt to create study materials in different forms for different audiences.

In the second assignment, further research was conducted in the best medium to convey Quantum Mechanical phenomenon to perspective students. Virtual Reality was the focus of the literature search which led to many fruitful results. With the advent of Virtual Reality, many complex physics and chemistry phenomenon have benefitted from the technology. Visualization techniques and direct manipulation of the Virtual World by the user have allowed students to comprehend complex subjects not from mathematical or cognitive models, but from directly manipulating the variables and coefficients in the underlying math by simply exploring the virtual world. Further research will concentrate on methodologies and teaching essentials needed to create a study course for a complex subject, such as quantum Mechanics. Creating a guideline for course creation can standardize and simplify integration of quantum Computing techniques into schools and universities.

1.2 Papers

1) *Reference* – Pal, A., Chandra, S., Mongia, V., Behera, B. K., & Panigrahi, P. K. (2018). Solving Sudoku Game Using Quantum Computation. Retrieved from https://www.researchgate.net/profile/Bikash_Behera4/publication/326978036_Solving_Sudoku_game_using_a_hybrid_classical-quantum_algorithm/links/5b6f040992851ca65055deb1/Solving-Sudoku-game-using-a-hybrid-classical-quantum-algorithm.pdf.
   Search – This article was retrieved from Google scholar search.
   Summary – The authors (Pal et al., 2018) describe an algorithm for solving a Sudoku puzzle in a quicker time on a quantum computer than classical computers. Additionally, the authors suggest a method for humans to utilize quantum logic in order to help them solve Sudoku puzzles manually.
   Takeaways – The main takeaway from this article is the idea of encoding a commonly understood game in Quantum Computing. By presenting everyday games and ideas in Quantum Computing code, students can make the transition form Classical computing much quicker and easier.
2) *Reference* – Nagy, M., & Nagy, N. (2012). Quantum Tic-Tac-Toe: A Genuine Probabilistic Approach. Retrieved from https://www.scirp.org/html/4-7400990_24755.htm.
   Search – This article was retrieved from Google scholar search.
   Summary – The authors (Nagy and Nagy, 2012) propose a quantum take on the classical Tic-Tac-toe game. The assumption is that quantum entanglement and the intrinsic probabilistic nature of Quantum Mechanics may provide a new reinvigorated view of the classic game Tic-Tac-Toe.
   Takeaways – The main takeaway from this article is that classical games can provide a new view into quantum computing. Instead of inventing new applications and games for quantum computing, classical applications can provide the necessary context for users to become comfortable with probabilistic nature of quantum mechanics.
3) *Reference* – Mason, B., Dębowska, E., Arpornthip, T., Girwidz, R., Greczyło, T., Kohnle, A., ... & Silva, J. (2015). Report and recommendations on multimedia materials for teaching and learning quantum physics. Teaching/learning Physics: Integrating Research into Practice. Retrieved from https://research-repository.st-andrews.ac.uk/handle/10023/6943.
   Search – This article was retrieved from Google scholar search.

Summary – The authors (Mason et al., 2015) summarize a summary and review of multimedia-based learning materials for Quantum Mechanics. The authors note that programming languages for these sources are becoming increasingly obsolete. Many mobile device applications are low-tech, only providing demonstrations without much control or interactivity. Additionally, although video content was found to be useful, it did not contain the "interactivity, student engagement, immediate feedback, and multi-model features" (Mason et al, 2015) required for good absorption of Quantum Mechanics study material.

Takeaways – The main takeaway from this paper is that there is an immense need for good multi-media content to facilitate understanding and learning of Quantum Mechanics. The current content may be good, but it may not be maintained for many years, may not have the necessary interactive features, and may not be complete as required by modern standard for Quantum Mechanics education. Opportunities for advancing the field of Quantum Mechanics education are numerous.

4) *Reference* – Kontogeorgiou, A. M., Bellou, J., & Mikropoulos, T. A. (2008). Being inside the Quantum Atom. PsychNology Journal, 6(1). Retrieved from http://www.academia.edu/download/7916180/10.1.1.151.7994.pdf.

   Search – This article was retrieved from Google scholar search.

   Summary – The authors (Kontogeorgiou et al., 2008) explore the use of an Educational Virtual Environment (EVE) with 38 students. The EVE is utilized to put the student in the perspective of a Quantum Atom. Mainly, the EVE was successful in providing mental images for the students, to supplement the study material which requires cognitive understanding.

   Takeaways – The main takeaway from this article is that visual aids are a vital part of conveying complex topics to students. By utilizing Virtual Reality, such visual aids can be crafted and explored by students in way impossible by other means.

5) *Reference* – Passon, O. (2004). How to teach quantum mechanics. European journal of physics, 25(6), 765. Retrieved from https://iopscience.iop.org/article/10.1088/0143-0807/25/6/008/pdf.

   Search – This article was retrieved from Google scholar search.

   Summary – The author (Passon, 2004) describes a case for an alternate way for teach Quantum Mechanics. Most lecture material focuses on highlighting the differences between classical and Quantum Mechanics. (Poisson, 2004) argues a better way to teach the advanced topic is to build upon the current knowledge of the student and draw continuation logic from classical physics to Quantum Mechanics.

Takeaways – The main takeaway from this paper is that it is possible to teach Quantum Mechanics from different angles. There is not a one-stop recipe for Quantum Phenomenon teaching.

6) *Reference* – Hobson, A. (2005). Electrons as field quanta: A better way to teach quantum physics in introductory general physics courses. American Journal of Physics, 73(7), 630-634. Retrieved from http://www.phys.utk.edu/courses/Spring-2014/macek-601/AJPHobson2005.pdf.

   Search – This article was retrieved from Google scholar search.

   Summary – The author (Hobson, 2005) suggests a teaching methods for Quantum Mechanics whereby a different view of classical physics presents a smooth introduction to Quantum Phenomenon. Specifically, learning of electron effects on the fields that they occupy, directly links to quantum effects that are observable through the "double-slit" experiment.

   Takeaways – the main takeaway from this paper is that there are many way to teach Quantum Theory. Considering Quantum Physics can explain some classical physics phenomenon, it is evident that there must be a way to ease a student into Quantum Mechanics by properly reforming their understanding of Classical Physics.

7) *Reference* – Robblee, K. M., & Gerald Abegg, P. G. (1999, March). Using computer visualization software to teach quantum science: the impact on pedagogical content knowledge. In Papers presented at the annual meeting National Association for Research in Science Teaching March, 1999 (p. 11). Retrieved from https://perg.phys.ksu.edu/papers/narst/QM_papers.pdf#page=13.

   Search – This article was retrieved from Google scholar search.

   Summary – The authors (Robblee and Abegg, 1999) present a case for the use of Quantum Science Across Disciplines (QSAD) software for high-school chemistry teachers in introducing Quantum Phenomena to students. The teachers attended a workshop and were followed up with surveys about their interpretation and integration of the software into their classroom. Most teachers positively responded to the training and the software, finding that the visual representation helped in information retention.

Takeaways – The takeaway from this paper is that teachers are not armed with the best tools to introduce Quantum Theory to students. Even basic training and visualization tools better prepare the teachers and aid the students in conceptual understanding of Quantum Phenomenon.

8) *Reference* – Lim, K. F. (2003). Using spreadsheets to teach quantum theory. New Directions in the Teaching of Physical Sciences, (1), 16-19. Retrieved from https://journals.le.ac.uk/ojs1/index.php/new-directions/article/view/386.
   Search – This article was retrieved from Google scholar search.
   Summary – The author (Lim, 2003) proposes using spreadsheets as the medium to introduce students to the Schrodinger Equation; one of the fundamental equations of Quantum Mechanics. By modifying the equations, coefficients, and variables in the spreadsheet the students can learn how wave functions can become quantized.
   Takeaways – The main takeaway from this article is that even rudimentary computer applications can help students understand Quantum Phenomenon. The important feature of the application is allowing the student to manipulate and explore the variables controlling the Quantum Phenomena. More specifically, this feature can be expanded to Virtual Reality. If manipulating variable sin spreadsheets is a successful teaching method, taking control of a Quantum Virtual Environment should provide students with an even better learning environment.
9) *Reference* – Hamari, J., Shernoff, D. J., Rowe, E., Coller, B., Asbell-Clarke, J., & Edwards, T. (2016). Challenging games help students learn: An empirical study on engagement, flow and immersion in game-based learning. Computers in human behavior, 54, 170-179. Retrieved from https://www.sciencedirect.com/science/article/pii/S074756321530056X.
   Search – This article was retrieved from Google scholar search.
   Summary – The authors (Hamari et al, 2016) explore the effects of engaging in a challenging game on learning objectives for students. The results show that challenging education games increate engagement, immersion, and interest in complex subjects. Games provide a medium where challenges can be adapted to the skill of the player, thus adapting to the needs of each individual student.
   Takeaways – The main takeaway form this article is that students have different levels of knowledge and skill sets. A teacher can not provide the

individualization required in order to bring up every student to their individual level of knowledge. Thus a game-supplemented teaching curriculum could provide the necessary medium to provide the best understanding of an advanced concept for each student.

10) *Reference* – Anupam, A., Gupta, R., Naeemi, A., & JafariNaimi, N. (2017). Particle in a box: An experiential environment for learning introductory quantum mechanics. IEEE Transactions on Education, 61(1), 29-37. Retrieved from https://ieeexplore.ieee.org/abstract/document/7999225.
Search – This article was retrieved from Google scholar search.
Summary – The authors (Anupam et al, 2017) present a study of a game whereby a student can take on the avatar traveling between classical and quantum worlds. The game focuses on demonstrating the "Particle-In-A-Box" phenomenon of Quantum Mechanics. The game significantly increased a student's comprehension of Quantum Mechanical concepts.
Takeaways – The main takeaway from this paper is that computer games simulating Quantum Mechanical phenomenon significantly increase the comprehension of a student in understanding Quantum phenomena. Considering that most students will not receive the necessary mathematical foundations to fully comprehend Quantum Physics to their full extent, game-based learning may be the best way to introduce Quantum Mechanics to students.

11) *Reference – Pedersen, M. K., Skyum, B., Heck, R., Müller, R., Bason, M., Lieberoth, A., & Sherson, J. F. (2016). Virtual learning environment for interactive engagement with advanced quantum mechanics. Physical Review Physics Education Research, 12(1), 013102.* Retrieved from https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.12.013102.
Search – This article was retrieved from Google scholar search.
Summary – The authors (Pederson et al, 2016) present an study of the virtual learning environment "StudentResearcher". This application incorporated simulations, quizzes, lectures, videos, and games for the purpose of learning Quantum Mechanics on an undergraduate level. The application was well received by students and their overall GPA was noted to increase as their understanding of the complex subjects became well founded.
Takeaways – The main takeaway from this paper is that there is a variety of content that is required in order to cement knowledge in a student. Taking a one-only approach to teaching advanced subjects will not work. Instead, a

combination of lecture material, hands-on activities, game, and interaction s required in order to provide the necessary feedback to construct the correct mental model and understanding of Quantum Mechanics.

12) *Reference* – Raghuvanshi, A., Fan, Y., Woyke, M., & Perkowski, M. (2007, May). Quantum robots for teenagers. In 37th International Symposium on Multiple-Valued Logic (ISMVL'07) (pp. 18-18). IEEE. Retrieved from https://ieeexplore.ieee.org/abstract/document/4215941.
Search – This article was retrieved from Google scholar search.
Summary – The authors (Raghuvanshi et al., 2007) provide a compelling argument to utilize Quantum Computing in simple Lego based robtics, in order to teach teenagers about Quantum Computing. Lego robotics are simple 6-ais robots, but the intelligence behind their trajectory paths can be offset to a Quantum Computer to evaluate. Namely, the Grover algorithm is used for path planning and traversal by the robots.
Takeaways – The main takeaway form this article is that there may be applications available in physical games which may allow one to learn Quantum computing better. Most papers focus on software and virtual applications to present Quantum phenomena and concepts to students. However, utilizing Lego robotics in order to present Quantum Grover's algorithm is an application of Quantum Computing with effects in the classical physical universe.

13) *Reference* – Chiarello, F. (2015, October). Board games to learn complex scientific concepts and the" Photonics Games" competition. In Proceeding of the European Conference on Games Based Learning 2015, Academic Conferences International Limited (pp. 774-779). Retrieved from https://www.researchgate.net/profile/Fabio_Chiarello/publication/286876922_Board_Games_to_Learn_Complex_Scientific_Concepts_and_the_Photonics_Games_Competition/links/576bc9dc08ae72f920718e5f.pdf.
Search – This article was retrieved from Google scholar search.
Summary – The author (Chiarello, 2015) presentas a study of three board games played by 1000 students and the results of studying the effects of playing these games. The students were generally found to be more motivated, interested in the concepts behind the game, and sparking deeper understanding in underlying concepts.
Takeaways – The main takeaway from this study is the fact that Quantum phenomena require different game rules and sets in order to be best understood. Each game can present a different level and conept of understanding leading

to a buildup of a full mental model. Most important, the games sparked student interests in continuing to study the subject.

14) *Reference* – López-Incera, A., & Dür, W. (2019). Entangle me! A game to demonstrate the principles of quantum mechanics. American Journal of Physics, 87(2), 95-101. Retrieved from https://aapt.scitation.org/doi/abs/10.1119/1.5086275.

    Search – This article was retrieved from Google scholar search.

    Summary – The authors (Lopez-Incera and Dur, 2019) present a study of the "Entangle me!" game and the outcome of students playing it. The game is intended to teach entanglement, quantum states, and stochastic behavior of quantum bits. The game assumes the students are rea scientists and encourages scientific experimentation and theorization by the players.

    Takeaways – The main takeaway form this paper is that even difficult subjects are capable of being taught using game-based teaching. Additionally, students do nto necessarily have to "play" the game, but can still retain their inquisitee mind by being scientific, even within the game.

15) *Reference* – Buerkle, A., Havens, V., Corrigan, D., & Bellis, M. (2020). A Quantum Mechanics Board Game. Bulletin of the American Physical Society. Retrieved from https://meetings.aps.org/Meeting/APR20/Session/D21.49.

    Search – This article was retrieved from Google scholar search.

    Summary – The authors (Buerkle et al, 2020) present a game by which students can follow pioneering scientists in the Quantum Mechanics field. The student gets to conduct some of the same experiments which lead to understanding Quantum phenomena.

    Takeaways – the main takeaway from this paper is that student can learn best by following the same logical trails the founders of the field in order to build their understanding of Quantum Mechanics. As the student gains a deeper understanding, their mental model of advanced concepts is properly shaped for further knowledge to be imparted outside of the game environment, through lectures and further studies.

1.3 Synthesis

Largely, game-based study material present excellent sources of teaching students the basics of Quantum Mechanics. Certain virtual game based learners allow students to act as particle or avatars in the quantum world, allowing mental concept models to be build which guide the student to correct understanding.

Most articles begin with the fact that students generally do not have advanced physics knowledge of the Quantum world and also do not require any formal training in order to learn the fundamentals. Through gamification of Quantum Mechanics the articles cited display that students gain increased interest, comprehension, and enthusiasm by playing targeted learning games in addition to formal lecture and study materials.

1.4 Reflection

Finding sources becomes increasingly more difficult as the focus of research narrows down. From studying general Quantum Mechanics topics, to diving deep into teaching advanced concepts, the task of researching is becoming more and more complex.

More specifically, as most article conclusions call out for more academic research into the topic, it is evident that a dead-end is nearing where there is simply a lack of resources in answering the fundamental question being researched. Mostly, the task at hand now is to collect as man opinions about a specific topic as possible, in order to quantify which theory is best represented. Thus, a certain aspect of research can be further explored as it is most purported by the current scientific body.

1.5 Planning

The plan going forward is to collect, analyse, and organize all research conducted from the past three assignments. The information will be categorized and dissected into the concepts which worked for teaching advanced Quantum Computing topics. Afterwards, a survey will be conducted on the Georgia Tech's student body in order to determine the best course forward in creating content for Quantum Computing course.

The findings from the survey will be summarized and a best course plan will be suggested in the summary and conclusion. As such, a standardized plan, supported by the past two decades of research can be proposed in order to create an effective, interactive, and functional class for future students. Considering Georgia Tech is on the forefront of Educational Technology, it is vital that a class targeted towards the boundary of current technology is structured in the best, most effective way possible.

2 ACTIVITY

2.1 Background Information

Quantum Computing is the next fundamental breakthrough in technological innovation. Quantum Mechanics and Computing involve complex mathematical formulations, comprehension of phenomenon unlike those met in everyday life, and a different way of thinking counterintuitive to modern standards. Even Einstein was perplexed by Quantum Phenomena but not even he could predict how impactful this field would be to our technological advancements (Bembeneck, 2019). The teachers and students of modern-day Schools and universities are beginning to introduce Quantum Theory into their classrooms more regularly and are preparing the next generation of scientists and engineers to integrate and advance this technology further in the coming years.

2.2 General Problem Statement

The general problem is that there is no standardized, efficient way to teach advanced topics, such as Quantum Mechanics, resulting in poorly prepared students with poor understanding and low interest in exploring the field further entering into academia, research and the general workforce that may use the technology.

2.3 Scholarly Support

(Deslauriers, 2011) Demonstrates that certain teaching methods, efficient for teaching classical concepts, are less effective than other in teaching advanced subject such as Quantum Mechanics. Consequently, utilizing proper teaching methods allows student to gain interest, knowledge, and information retention about a topic even if the underlying concepts are complex. (Krijtenburg-Lewerissa et al, 2017) furthermore describes a deeper fundamental problem in the lack of proper teaching methods of the academics charged with presenting knowledge of Quantum Computing to undergraduate students.

2.4 Specific Problem Statement

The specific problem is, in addition to poor understanding, lack of interest, and poor retention rates, there does not exist a standard, best practice for teaching Quantum Computing to perspective students in an efficient and effective way resulting in loss of momentum in newly minted Quantum Computing experts and early adopters.

2.5 Closing Commentary

(Baily, 2014) summarized the current state of teaching Quantum Physics best, instructors vary in their approaches, different approaches have different impacts and without feedback, student perceptions may lead to incorrect interpretations and conclusions about the subject being taught. (Westfall, 2018) recognizes that most teaching material on the subject is written by, and for, other experts in the field. Without reassessing how to teach advanced concepts, what medium should best be used to present complex information, who is best qualified to teach this information and what pieces of the material are most critical to be taught, the integration of Quantum technology into mainstream may be delayed by decades. If students do not contain a fundamental understanding and genuine interest in the technology, they will be less likely to acclimate to using the technology in their future careers, stalling further development and research in the field.

3 REFERENCES

1) Bembenek, S. (2019, January 9). Why everyone can - and should - learn quantum mechanics. Retrieved from https://www.salon.com/2018/11/18/why-everyone-can-and-should-learn-quantum-mechanics/
2) Deslauriers, L., & Wieman, C. (2011). Learning and retention of quantum concepts with different teaching methods. Physical review special topics-physics education research, 7(1), 010101. Retrieved from https://journals.aps.org/prper/pdf/10.1103/PhysRevSTPER.7.010101
3) Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., & Van Joolingen, W. R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education. Physical review physics education research, 13(1), 010109. Retrieved from https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.13.010109
4) Baily, Charles & Finkelstein, Noah. (2014). Teaching Quantum Interpretations: Revisiting the goals and practices of introductory quantum physics courses. Phys. Rev ST - PER. 11. 10.1103/PhysRevSTPER.11.020124. https://arxiv.org/abs/1409.8503

5) Westfall, L., & Leider, A. (2018, November). Teaching quantum computing. In Proceedings of the Future Technologies Conference (pp. 63-80). Springer, Cham. Retrieved from http://csis.pace.edu/~ctappert/srd2018/2018PDF/a5.pdf