

Assignment 1: Teaching Quantum Computing

Sergiy Palguyev

sergiy.palguyev@gatech.edu

Abstract—Quantum Mechanics and Quantum Computing is an extremely complex field, challenging even the brightest minds of the last century such as Albert Einstein and Richard Feynman. The technology is on the cusp of broad general market availability and the need for professionals to utilize the machines will be needed in the near term. As such, there is a need for a resource focused on technology professionals focusing on "How" to use the machine, instead of the underlying physics behind it.

1 RESERCH LOG

1.1 Background

Integrating or expanding existing systems with new technological advancements often proves to be quite difficult. Partially this is due to the slow pace of adaptation in certain industries. On the other hand, the education of engineering professionals is sometimes improperly targeted, often focusing on theory, rather than practical use and integration methods into a working system. Quantum Computing is a fascinating field, poised to integrate into mainstream technology stack within the coming years.

The larger part of education on quantum computing either focuses broadly on simple concepts or dives deep into theoretical quantum mechanics, neither of which help an engineer integrate a quantum computing device into their system. As an engineer, expanding my knowledge of up-and-coming technologies is a necessity in order to modernize and integrate into the current technology stack of my workplace.

The goal for exploring Education Technologies is to find an area of technological advancements which can be simplified and presented in a way which makes it clear for other engineers how to understand, integrate and make best use of a technology without diving deep into its inner workings.

1.2 Papers

- 1) *Reference* – Hughes, C., Isaacson, J., Perry, A., Sun, R., & Turner, J. (2020). Teaching Quantum Computing to High School Students. arXiv preprint arXiv:2004.07206. Retrieved from <https://arxiv.org/abs/2004.07206>.

Search – This paper was found through Google Scholar, searching for paper related to teaching quantum Computing.

Summary – The author (Hughes, 2020) provides an analysis of teaching a Quantum Computing curriculum to a cohort of students between the ages of 15-18. The course was taught over the course of 5 days, covering the basic topics of Quantum bits (qubits) as well as some applications which they may be applied to. Overall, the course was successful as students came out of the class with more knowledge and more interest in Quantum Mechanics and Quantum Computing.

Takeaways – The material presented assumed basic, but necessary knowledge of physics principles and proved to be a success in sparking interest in Quantum Computing. The biggest limitation, noted, was the time constraint in bringing all students up to a similar knowledge level. The key takeaway was a note that trying to let the student read the lecture material on their own time, but then running practice and laboratory exercises in class seemed much more favorable and fruitful, rather than spend a portion of the class lecturing the material.

- 2) *Reference* – Bleicher, A., & Quanta Magazine. (n.d.). Quantum Computers Struggle Against Classical Algorithms. Retrieved from <https://www.quantamagazine.org/quantum-computers-struggle-against-classical-algorithms-20180201/>

Search – This article was found on Google Scholar, searching for quantum algorithms.

Summary – The author (Bleicher, 2018), provides an analysis of popular misconceptions about Quantum Computers and the current state of the art classical computers algorithmic power. Quantum Computers, (Bleicher, 2020) claims, are capable of powerful computational complexity, but the line where their supremacy is determined varies, as advances in Quantum Computing inadvertently demonstrate untapped and powerful potential in classical computing as well. Classical computers, still do, and always will have a place in Computation theory alongside Quantum Computers for specialized tasks.

Takeaways – In essence, advancements in quantum computing has brought upon realizations of untapped power of classical computers. This fact continues to move the defining line of what is "Quantum Supremacy" and when can it be achieved. Even when Quantum Supremacy is established, the problems being solved by these Computers will still be far from applicable to daily life, as popular media would have us believe.

- 3) *Reference* – 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>

Search – This source was found on Google Scholar for teaching Quantum Computing.

Summary – This author (Deslauriers, 2011) analyses the methods taught to students of advanced concepts in quantum computing and their retention of taught material. The main topics learned were conceptual rather than factual and the teaching methods compared were standard lecture and interactive engagement. Interactive engagement produced noticeably better retention rates in students while understanding appeared to remain similar.

Takeaways – The takeaway from this study shows that interactive learning for advanced concepts is a better approach to teaching advanced studies. Traditional lecture style teaching may still be effective, but the retention rate of students is not as high as interactive teaching methods.

- 4) *Reference* – 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>

Search – This source was found on Google Scholar for teaching Quantum Computing.

Summary – The author (Krijtenburg-Lewerissa, 2017) of this article analyses a number of articles on the teaching methods, struggles and outcomes of teaching quantum mechanics to undergraduate students. The outcome of the study shows a lack of assessment tools and general grasp and understanding of basic quantum mechanics which a general failure to standardize an effective teaching method for such advanced concepts throughout the field. The author concludes with a call for further empirical research into the matter.

- Takeaways* – The best way to teach quantum computing is still poorly understood. Study in this area shows a need, not only for comprehensive background knowledge, but also for a well-established teaching technique to properly establish a solid foundation for undergraduate students in the field.
- 5) *Reference* – Freericks, J. K., Vieira, L. B., Cutler, D., & Kruse, A. (2017). Teaching quantum mechanics to over 14,000 nonscientists. arXiv preprint arXiv:1712.02660. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1712/1712.02660.pdf>

Search – This source was found on Google Scholar for teaching Quantum Computing.

Summary – The author (Freericks, 2017) of this article describes the creation of a MOOC for teaching quantum mechanics without requiring any advanced background knowledge in Mathematics or Physics. The success of the MOOC is presented as having taught over 14000 students with the reiterated factor of the course as visual simulations displaying how the "spooky" quantum effects occur and how different logic gates of the Quantum Computer affect the outcome.

Takeaways – The takeaway from this article is that interactive visual aids can help break down barriers of understanding which would typically require advanced knowledge. Visually stimulated understanding relieves a student from having to understand the physics and mathematics of an interaction and simple allow him to focus on the cause and effect of an action.

- 6) *Reference* – Kohnle, A., Douglass, M., Edwards, T. J., Gillies, A. D., Hooley, C. A., & Sinclair, B. D. (2010). Developing and evaluating animations for teaching quantum mechanics concepts. European journal of physics, 31(6), 1441. Retrieved from <https://arxiv.org/abs/1307.1484>

Search – This source was found on Google Scholar for teaching Quantum Computing.

Summary – The author (Kohnle, 2010) describes the study material created for teaching a first year undergraduate course in Quantum Mechanics. The paper focuses on emphasizing that advanced mathematics beyond Linear Algebra is not required and all concepts taught are accompanied by short articles and simulations to demonstrate the effect of concepts being studied.

Takeaways – The main takeaway from this article is that students can read about basic background on certain aspects of Quantum Mechanics on their own while solidifying their knowledge in class through experimentation and

simulation. It is evident that advanced mathematical proficiency is not required to grasp a basic understanding of Quantum Mechanics.

- 7) Reference – Mykhailova, M., & Svore, K. M. (2020, February). Teaching Quantum Computing through a Practical Software-driven Approach: Experience Report. In Proceedings of the 51st ACM Technical Symposium on Computer Science Education (pp. 1019-1025). Retrieved from <https://dl.acm.org/doi/pdf/10.1145/3328778.3366952>

Search – This source was found on Google Scholar for teaching Quantum Computing.

Summary – The author (Mykhailova, 2020) present an article on teaching Quantum Computing to undergraduate students through a software-driven approach. The teaching structure is focused on programming quantum algorithms rather than lectured on quantum mechanics. The goal of the study is to allow students early exposure to the difference and applicability of quantum computing to real world scenarios. The course was effective and intellectually stimulating to the students, while at time overwhelmingly challenging due to time constraints.

Takeaways – The main takeaway from this study is that hands-on training in the application of quantum computing can be done separately, if not in parallel with learning about the Quantum Mechanics behind the inner working of the algorithms. Advanced computing prowess appears to require advancing further knowledge, but Introductory level exposure can be attained without knowing the Physics behind the Quantum Computer.

- 8) Vos, J. (2020) The Impact of Quantum Computing on Software Development. Retrieved May 18, 2020, from <https://developer.oracle.com/java/quantum-computing.html>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (Vos, 2020) of the article describes the current state of software engineer, the need for quantum computing, and the case for why the two will coexist. Additionally, a rudimentary introduction if presented on Quantum Algorithm programming. Additionally, an example is presented how to integrate a call to a Quantum Computer within a JAVA program.

Takeaways – The main takaway form this article is the apparent fact of coexisting necessities between classical programming and Quantum Computing.

- The author (Vos, 2020) makes the case that Quantum Computing will not replace classical programming but will be relied on to provide the information necessary which classical computers are not capable of.
- 9) *Reference* – Tappert, C. C., Frank, R. I., Barabasi, I., Leider, A. M., Evans, D., & Westfall, L. (2019). Experience Teaching Quantum Computing. Association Supporting Computer Users in Education. Retrieved from <https://files.eric.ed.gov/fulltext/ED597112.pdf>
- Search* – This source was found on Google Search for teaching Quantum Computing.
- Summary* – The author (Tappert, 2019) analyses the teaching of Quantum Computing to graduate level students and those in high school. Each cohort was taught a different set of concepts of Quantum Computing. The conclusion drawn by the author (Tappert, 2019) indicated Quantum Computing to be a feasible subject to teach for undergraduate level students, relegating Quantum Mechanics to those interested in pure physics and unnecessary to learn for those learning only about Computing.
- Takeaways* – The main takeaway from this article is the lack of advanced Quantum Mechanics knowledge required to learn about Quantum Computing. It is important that although Quantum Computing is based on Quantum Mechanics, the understanding on Quantum Mechanics is not critical in order to make full use of Quantum Computing in building applications and drawing conclusions in cause and effect of the Quantum System.
- 10) *Reference* – 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>
- Search* – This source was found on Google Search for teaching Quantum Computing.
- Summary* – The author (Baily, 2014) analyses the effect that studying Quantum Mechanics has on student understanding. Student conception and visualization of Quantum interactions, the author claims, are often ignored by instructors as they focus on teaching the views of the researchers and scientists which invented the field. The author proposes a curriculum which addresses the needs, views and interpretation of the students in order to facilitate better understanding of the physics of Quantum Mechanics.

Takeaways – The main takeaway from this paper is that the instructors of Quantum Mechanics may structure their lessons around the thoughts and principles of the scientists which advance the field, without addressing the students understanding and conception of the concepts being taught. Additionally, the use of classical physics interpretation by the students is not seen as a crutch, but rather as a tool to allow students to facilitate a better understanding on quantum physics, rather than allowing students to form their own, sometimes wrong, interpretations.

- 11) *Reference* – 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/~ctapert/srd2018/2018PDF/a5.pdf>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (Springer, 2018) presents a set of concepts required for teaching quantum physics to high school students. Seeing a trend that most resources are written for and by physicists and mathematicians, the author presents an interpretation of basic Quantum mechanics, keep necessary information for a full grasp while removing unnecessary details, only of interest to quantum physicists. The author prepares the subjects discussed as a possible starting point for developing a course of study material for high school level students.

Takeaways – The main takeaway of this paper is that a large portion of available material is not targeted for beginners of those of interest in learning about Quantum Computing. It is possible to narrow down the scope of Quantum Computing concepts in order to teach the material without having to weigh down the student with unnecessary mathematical and physics that is not required.

- 12) *Reference* – Barnes, M.B., Garner, J. & Reid, D. The Pendulum as a Vehicle for Transitioning from Classical to Quantum Physics: History, Quantum Concepts, and Educational Challenges. Science & Education 13, 417–436 (2004). <https://doi.org/10.1023/B:SCED.0000041829.61208.58>
<https://link.springer.com/article/10.1023/B:SCED.0000041829.61208.58#citeas>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (Barnes, 2004) presents a classical interpretation of a pendulum for the purpose of transitioning a student's understanding into Quantum Mechanics. The pendulum's many interpretations into waves and oscillations are presented as a good transition point into understanding quantum effects and the physics of Quantum Mechanics. The author leads to propose a curriculum for undergraduate students in transitioning the understanding of a student of classical Physics, to Quantum Mechanics.

Takeaways – The main takeaway from this article is the idea that there is room for classical physics concepts, interpretations and example to represent and provide an understanding for quantum phenomena. Visual aids are always a useful tool in the teaching curriculum and from the point of the author, the pendulum is one which was used by the original inventors of Quantum Mechanics. This should be the tool used in classroom to produce understanding on Quantum Phenomenon by students as well.

- 13) *Reference* – Marshman, E., & Singh, C. (2015). A Framework for Understanding the Patterns of Student Reasoning Difficulties in Quantum Mechanics. arXiv preprint arXiv:1504.02042. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1504/1504.02042.pdf>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (Marshman, 2015) analyses the possible reasons why grasping and constructing a well founded understanding of Quantum Mechanics has been difficult for students. Problem categorization in quantum mechanics and physics, problem solving, inconsistent context reasoning, and difficulties in multi-part problems are some of the possible causes claimed by the author. The concluding thought by the author is that students should have a feedback loop where their self-explanation is discussed and corrected by the instructor in order to realign the student's concept view with actual Quantum phenomena.

Takeaways – The main takeaway from this article is the need for student feedback loop. The student may grasp certain concepts and build on top of them a model of understanding of the Quantum World. If their understanding is flawed, all further concepts learned may become invalid. It is important for the student to receive feedback on their interpretation and mental model in order to properly continue building up their knowledge.

- 14) *Reference* – Benicio de Barros Neto (1984). Dice throwing as an analogy for teaching quantum mechanics. *Journal of Chemical Education* 1984 61 (12), 1044 DOI: 10.1021/ed061p1044. Retrieved from <https://pubs.acs.org/doi/pdf/10.1021/ed061p1044>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (de Barros Neto, 1984) describes an analogy of Quantum Mechanics to dice throwing. The most prominently important aspect of Quantum Computing is the act of "measurement" and thus the comparison to throwing a die and only caring about the upward face is presented. Furthermore, (de Barros Neto, 1984) presents a case to expand the analogy to other quantum behavior.

Takeaways – The main takeaway for this article is the idea of conceptualizing quantum behavior as a die, with measurement of the Qubits to equate to that of the die face when the die lands. This is an interesting interpretation as it directly talks to the act of "measuring" the outcome as that is the main purpose and final result expected of the Quantum Computer.

- 15) *Reference* – Justin D. Weisz, Maryam Ashoori, and Zahra Ashktorab. 2018. Entanglion: A Board Game for Teaching the Principles of Quantum Computing. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '18)*. Association for Computing Machinery, New York, NY, USA, 523–534. DOI: <https://doi.org/10.1145/3242671.3242696> Retrieved from <https://dl.acm.org/doi/pdf/10.1145/3242671.3242696>

Search – This source was found on Google Search for teaching Quantum Computing.

Summary – The author (Weisz, 2018) presents a game called Entanglion, created in order to teach middle to high-school students' basic interactions of entanglement in Quantum Physics. Although almost a third of the students did not respond or participate, the majority of those that did found the game educational and fun. The game does not require any background in the quantum mechanics or physics in order to be played.

Takeaways – The main takeaway from this article is the idea that even middle school students can be taught some basic ideas behind quantum computing which may spark an interest. Quantum Mechanics is a complex study of Quantum effects, one that does not need to enter the classroom in order to teach the basics of the Quantum world to students. The invention of this

game may produce further research into teaching Quantum effects to children of even younger ages.

1.3 Synthesis

Throughout the research presented, it is evident that Quantum Computing is an important technology, on the cusp of entering into mainstream innovation. The study of Quantum Computing and Quantum Mechanics is a very complex endeavor which generally requires graduate-level education and advanced training.

The sources discussed above demonstrate that advanced knowledge of Quantum Mechanics and Physics can often be bypassed in order to introduce students of under-graduate, High-School and sometimes even Middle-School ages to the concepts behind Quantum Mechanics.

All papers cited present some aid for teaching Quantum Mechanics, whether in the form of simulation, visual representation, Classical Physics examples or other means, it is evident that simply lecturing on the topic of Quantum Mechanics is not an effective way to present the topic. Many studies found that simply reading background material away from class, followed by laboratory practice in the lessons learned provided a high retention and interest rate in Quantum Theory and Quantum Computing.

Hands on experience proved most fruitful and stimulating for most students. Whether direct Quantum Algorithm programming or playing aboard game by Middle-School ages children, hands on experience allowed for better concept retention and understanding amongst all surveyed groups.

Instructors of Quantum Mechanics have determined that many concepts do not require advanced knowledge of Math or Physics in order to be well grasped by students. However, a feedback loop from the student to correct their understanding was required. Afterall, Quantum Mechanics do not work like anything else in our known world, thus a misinterpretation by the student may pave the way to wrong interpretation of more advanced topics and a loss in concept retention.

All articles point to the need to advance the understanding of Quantum phenomena as the evolution of Classical Computing to Quantum Computing is on the horizon.

1.4 Reflection

The beginning of this research focused more on learning about Quantum Computing in general. As such, the multitude of articles, MOOC classes and journals on the basic concepts and ideas being Quantum Mechanics were reviewed and evaluated. Although the content presented was similar, the presentation itself led to confusion, reinterpretation and a general loss of interest due to some article's presentation of the content.

Due to this phenomenon, the research interest shifted from Quantum Computing itself, to exploration of how advanced subjects, such as Quantum computing, can be presented and taught to a wide audience. From undergraduate-level Computer Scientists, to adult non-scientists, to Middle—School students. A common trend appeared across multiple sources, that teaching Quantum Computing and Quantum Mechanics is still a field under development, but one that does not require advanced understanding of Quantum Physics. Simply, there is a lack of consistency and understanding of how best to present such topics as most material existing to date was created by and for other Mathematicians and Physicists in the field.

1.5 Planning

The plan for continued research is to determine that absolute basic building blocks of Quantum Computing. Additionally a definition of target cohorts and their knowledge level must be determined in order to research how various knowledge and life experience may affect comprehension of material. Furthermore, the subjects of Quantum Computing will be categorized and separated to determine which concepts must be learned, which can be taught to a broad audience, and which can be left to Advanced Users and academics.

By determining what to teach and who to teach it to, the rest of the research shall focus on determining best practices and methods for teaching advanced concepts. It is already evident from the sources cited above that simulation, demonstration, live feedback, exercises and analogies serve best to create comprehensive understanding for students. However, an exact characterization of How and Why these methods work does not seem to exist. Determining the best path forward for teaching Quantum Computing to the target cohort will become the main focal point of further research.

2 ACTIVITY

2.1 Paper 1 - Hughes, C., Isaacson, J., Perry, A., Sun, R., & Turner, J. (2020). Teaching Quantum Computing to High School Students. arXiv preprint arXiv:2004.07206. Retrieved from <https://arxiv.org/abs/2004.07206> .

2.1.1 *Need*

There is a need to introduce Quantum Mechanics at an earlier age in order to garner interest in the field by the time student become under-graduate and graduate level academics in the STEM field.

2.1.2 *Method*

The method for filling this need was to create a five-day introductory course in Quantum Mechanics. This course was created to introduce students to a wide array of concepts from Qubits to Quantum Algorithms in Quantum Computing.

2.1.3 *Audience*

The audience was a class of 20-25 students ranging in age from 15-18 years old. None of the student had any knowledge of advanced Quantum Physics or Mathematics but the material does assume a basic knowledge of magnetism, electricity and wave of the high-school level.

2.1.4 *Results*

The results of the study were positive, with many students expressing a better understanding of Quantum Mechanics concepts and a higher level of interest in pursuing further education in the matter.

2.1.5 *Critique*

This paper presents a compelling case for teaching fundamental Quantum Mechanics at the high-school level. Several questions arose, reading through the paper there appears to be a lack of explanation as to how/why certain material was chosen to be taught, or ignored in the curriculum as well as further detail into content presentation at each concept. It is evident that certain concepts were better perceived than others, but the age range of 15-18 provides a very wide range of understanding of Classical Physics, which may skew certain comprehension of quantum phenomena.

2.2 Paper 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>

2.2.1 Need

There is a need to understand how content presentation of advanced topics correlated with the retention rate of the students being taught. Quantum Mechanics is a topic which is very different and represents a perfect candidate for evaluating different teaching principles.

2.2.2 Method

The method for evaluating conceptual retention was to observe student retention rates after 6 and 18 months after taking a specific class. The class was taught either in Interactive Engagement methods or through traditional lecturing.

2.2.3 Audience

The audience is a cohort of 60-80 undergraduate students being taught quantum physics concepts.

2.2.4 Results

The results supported the initial notion that material retention rates were good for both methods of teaching, but students with interactive engagement teaching method retained a better understanding of concepts learned for a longer period of time.

2.2.5 Critique

This paper presents a very good case for the interactive style of teaching. Many courses at the university level are taught as direct lectures without much student-teacher interactions and this article clearly shows that for critical material retention, Interactive Engagement may play a big role.

2.3 Paper 3 - Freericks, J. K., Vieira, L. B., Cutler, D., & Kruse, A. (2017). Teaching quan-tum mechanics to over 14,000 nonscientists. arXiv preprint arXiv:1712.02660. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1712/1712.02660.pdf>

2.3.1 Need

There is a need to introduce non-scientist adults to the concepts of quantum computing in order to increase interest and engagement with the topic and prepare for the next technological wave.

2.3.2 Method

The method proposed by the authors is creating a MOOC course, completely absent of advanced Mathematical or Physics concepts. The course, instead, comprises of an array of visual aids and simulations, allowing students to build visual concept models of quantum interactions, rather than worry about their mathematical formulations.

2.3.3 Audience

The audience includes over 14,000 enrollees of unknown ages with over 145 students which have completed the course.

2.3.4 Results

The results of the course seem like a success considering the advanced interest observed by the number of enrollees. This points to the fact that the material is welcoming and easily understood by incoming students, allowing for good retention and concept understanding.

2.3.5 Critique

There is a lack of determining the usefulness of the course to the students. Considering this is a MOOC course catering to an extremely broad audience, there is a lack of follow up to determine how useful this course is, and what students did with the knowledge afterwards.

2.4 Paper 4 - Mykhailova, M., & Svore, K. M. (2020, February). Teaching Quantum Computing through a Practical Software-driven Approach: Experience Report. In Proceedings of the 51st ACM Technical Symposium on Computer Science Education (pp. 1019-1025). Retrieved from <https://dl.acm.org/doi/pdf/10.1145/3328778.3366952>

2.4.1 Need

There is a need to introduce Computer Scientists to new concepts in Quantum Computing without overwhelming them with Quantum Mechanics and physics.

2.4.2 Method

The method chosen by the authors includes a course developed around hands-on training in implementing Quantum Algorithms.

2.4.3 Audience

The audience are undergraduate Computer Science students without previous experience in Quantum Computing or advanced Physics.

2.4.4 Results

The results were positive and slightly overwhelming. Students appeared to grasp initial understanding of Quantum Algorithms quickly, but became overwhelmed with advanced challenges.

2.4.5 Critique

The paper presents a good case for presenting a target audience of Computer Scientists with a deep dive directly into algorithmic development of Quantum Computing. This goes against the grain of tradition teaching of Quantum Computing which starts with an introduction to Quantum Mechanics. This seemed to work for most of the class, however the paper fails to detail exactly where the student began to feel challenged. This information can provide insight where the need to deeper understanding of Quantum Mechanics may be required before continuing further education in Quantum Algorithm development.

2.5 Paper 5 - Marshman, E., & Singh, C. (2015). A Framework for Understanding the Patterns of Student Reasoning Difficulties in Quantum Mechanics. arXiv preprint arXiv:1504.02042. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1504/1504.02042.pdf>

2.5.1 Need

There is a need to understand exact reasons for lack of concept retention in student of Quantum Computing. In order to better facilitate information retention, certain aspects of advanced Quantum Mechanics teaching must be better understood, in order to address the pitfalls in student understanding.

2.5.2 Method

The method proposed is a framework of empirical investigations and drawing parallels in the concept retention strategies and pitfalls for classical mechanics and quantum mechanics.

2.5.3 Audience

The audience are undergraduate level students.

2.5.4 Results

The framework proposed suggests that similar tools as those used in classical mechanics can be employed in the understanding of quantum mechanics as well. More importantly, student self-regulation, whereby a feedback loop in concept understanding is important in order to maintain a well-founded comprehension of concepts not observable in the surrounding world of the student.

2.5.5 Critique

This study provides great empirical evidence of how to guide content creation and presentation of Quantum Mechanical concepts to new students of the field. The authors present many possible pitfalls and challenges that may arise, but also correctly states that further research must be conducted in parallel with advancement of the field.

3 REFERENCES

- 1) Hughes, C., Isaacson, J., Perry, A., Sun, R., & Turner, J. (2020). Teaching Quantum Computing to High School Students. arXiv preprint arXiv:2004.07206. Retrieved from <https://arxiv.org/abs/2004.07206>.
- 2) Bleicher, A., & Quanta Magazine. (n.d.). Quantum Computers Struggle Against Classical Algorithms. Retrieved from <https://www.quantamagazine.org/quantum-computers-struggle-against-classical-algorithms-20180201/>
- 3) 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>
- 4) 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>
- 5) Freericks, J. K., Vieira, L. B., Cutler, D., & Kruse, A. (2017). Teaching quantum mechanics to over 14,000 nonscientists. arXiv preprint arXiv:1712.02660. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1712/1712.02660.pdf>
- 6) Kohnle, A., Douglass, M., Edwards, T. J., Gillies, A. D., Hooley, C. A., & Sinclair, B. D. (2010). Developing and evaluating animations for teaching quantum mechanics concepts. European journal of physics, 31(6), 1441. Retrieved from <https://arxiv.org/abs/1307.1484>
- 7) Mykhailova, M., & Svore, K. M. (2020, February). Teaching Quantum Computing through a Practical Software-driven Approach: Experience Report. In Proceedings of the 51st ACM Technical Symposium on Computer Science Education (pp. 1019-1025). Retrieved from <https://dl.acm.org/doi/pdf/10.1145/3328778.3366952>
- 8) Vos, J. (2020) The Impact of Quantum Computing on Software Development. Retrieved May 18, 2020, from <https://developer.oracle.com/java/quantum-computing.html>
- 9) Tappert, C. C., Frank, R. I., Barabasi, I., Leider, A. M., Evans, D., & Westfall, L. (2019). Experience Teaching Quantum Computing. Association Supporting

- Computer Users in Education. Retrieved from <https://files.eric.ed.gov/fulltext/ED597112.pdf>
- 10) 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>
 - 11) 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/~ctapert/srd2018/2018PDF/a5.pdf>
 - 12) Barnes, M.B., Garner, J. & Reid, D. The Pendulum as a Vehicle for Transitioning from Classical to Quantum Physics: History, Quantum Concepts, and Educational Challenges. *Science & Education* 13, 417–436 (2004). <https://doi.org/10.1023/B:SCED.0000041829.61208.58>
<https://link.springer.com/article/10.1023/B:SCED.0000041829.61208.58#citeas>
 - 13) Marshman, E., & Singh, C. (2015). A Framework for Understanding the Patterns of Student Reasoning Difficulties in Quantum Mechanics. arXiv preprint arXiv:1504.02042. Retrieved from <https://arxiv.org/ftp/arxiv/papers/1504/1504.02042.pdf>
 - 14) Benicio de Barros Neto (1984). Dice throwing as an analogy for teaching quantum mechanics. *Journal of Chemical Education* 1984 61 (12), 1044 DOI: 10.1021/ed061p1044. Retrieved from <https://pubs.acs.org/doi/pdf/10.1021/ed061p1044>
 - 15) Justin D. Weisz, Maryam Ashoori, and Zahra Ashktorab. 2018. Entanglion: A Board Game for Teaching the Principles of Quantum Computing. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '18)*. Association for Computing Machinery, New York, NY, USA, 523–534. DOI: <https://doi.org/10.1145/3242671.3242696> Retrieved from <https://dl.acm.org/doi/pdf/10.1145/3242671.3242696>