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Teaching Quantum Randomness to Middle School Students: A Two-Year Study (EoP/CP)

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Teaching Quantum Randomness to Middle School Students: A Two-Year Study (Evaluation)

Introduction

The integration of Quantum Information Science and Engineering (QISE) concepts into K-12 education offers a valuable opportunity to introduce students to cutting-edge scientific advancements and technologies shaping the future. As quantum technologies increasingly influence fields such as computing, communications, and materials science, there is a growing interest in exploring how foundational quantum concepts can be meaningfully introduced to pre-college students. National initiatives, including those supported by the Department of Defense and the National Science Foundation, emphasize the importance of raising awareness of QISE among students and educators. These efforts align with the National Quantum Coordination Office’s recommendation to expand pathways for QISE education by embedding quantum topics into existing curricula.

While the Next Generation Science Standards (NGSS) do not explicitly provide a framework to introduce QISE concepts at the middle school level, the scientific content recommended at this grade band is inherently flexible and adaptable. This flexibility enables educators to incorporate quantum-infused topics, such as quantum randomness, into physical science and mathematics lessons without requiring a complete overhaul of the curriculum. The NGSS emphasizes three-dimensional learning—disciplinary core ideas (DCIs), scientific and engineering practices (SEPs), and crosscutting concepts [1]—and this approach can serve as a foundation for developing activities that align with quantum concepts.

Middle school represents a pivotal stage for engaging students in foundational scientific ideas, as they begin to explore abstract and complex topics [2]. Research indicates that middle schoolers possess the cognitive ability to grasp simplified concepts, when challenging topics are introduced in age-appropriate and interactive ways [3], [4]. Furthermore, studies suggest that embedding quantum concepts into middle school curricula can not only enhance students' understanding of scientific principles but also cultivate curiosity and awareness of emerging scientific fields [3].

Notable work by [5] demonstrated that middle school science curricula can successfully integrate quantum concepts while maintaining alignment with NGSS standards. Their study focused on introducing foundational ideas in quantum computing, such as qubits and superposition, through simulation-based activities that connected theoretical concepts to real-world applications, such as drug discovery. These approaches highlighted the potential of quantum-focused lessons to engage students and deepen their understanding of both scientific principles and their technological applications.

Building on these insights, this paper aims to explore strategies to enhance middle school students’ conceptual understanding of selected quantum topics, with an emphasis on raising awareness of QISE advancements. Our approach leverages the inherent flexibility of middle school science content to introduce quantum topics in a way that is both accessible and meaningful. By focusing on concepts such as quantum randomness and their connections to broader scientific themes such as radioactive decay, we aim to provide educators with practical instructional tools to inspire students' curiosity and foster multidimensional engagement.

Instructional Context

Curriculum Design

In Tippecanoe County, IN, middle schools teach radioactive decay as part of their science curriculum. One thing to note about radioactive decay is that the apparent randomness observed in radioactive decay arises from quantum mechanical principles, specifically the probabilistic nature of quantum mechanics, so we chose radioactive decay as the pre-existing middle school curriculum that would receive a quantum concept infusion, via elaborating on this quantum randomness aspect.

To guide our creation of curriculum content, we turned to the NGSS [1]. We wanted the instructional content to start with concepts in classical randomness and probability before introducing quantum randomness. Examining the NGSS Performance Expectations (P.E.s), we found that MS-ESS1-4, The History of Planet Earth, exploring fossil records [1], and MS-ESS3-1, Natural Resources, emphasizing the uneven distribution of fossil records resulting from past geological processes [1] suited our aims. After assembling learning content aligned to these P.E.s, we looked at their DCIs, relevant SEPs, and crosscutting concepts. By considering these three things, we were better able to figure out how to present and sequence the content into lessons that conveyed an understanding of classical randomness and probability to students inside an overall context of radioactive decay (c.f. third, fourth, and fifth steps in [6]).

With the classical concepts covered, we turned to creating instructional content for the quantum concept. We wanted to introduce quantum randomness as a contrast to classical randomness and as an aspect of the real-world application of quantum mechanics, quantum computing, specifically quantum random number generators. Because we were now also dealing with computer science topics, we looked at state standards for teaching computer science topics in middle school, so that our content could align with those. Our instructional content creation was guided by the following state computer science standard and their associated core practices: 6-8. DI.2, 6-8. DI., 6-8. DI.4, and 6-8.CD.4 [7].

With all the content made, the final step was to assemble the entire curriculum package. To do this, we followed the design-based research methodology [8]. In the end, what we had was a middle school quantum infused curriculum that took a pre-existing unit on radioactive decay and added on coverage of quantum randomness. The major activities of our unit were: a lab exploring carbon dating aimed at establishing an understanding of half-life via a penny toss experiment and understanding quantum randomness by creating randomly colored artwork based on a real time data output of 0's and 1's from a quantum computer owned by [9].

The curriculum was designed to be implemented over 6.5 hours, distributed across multiple instructional sessions. Each session was structured to introduce a key concept, followed by hands-on activities and discussions to reinforce learning. The instructional format followed an inquiry-based approach, integrating both direct instruction and exploratory activities.

The curriculum included a combination of fixed instructional components (essential learning activities and assessments) and flexible components (where instructors could modify or expand on topics). There was a balance of fixed instructional components, such as core explanations of radioactive decay, half-life, and quantum randomness, with flexible elements that allowed teachers to adapt the content. While essential activities like the half-life simulation with coins and quantum random number generation remained consistent, instructors could modify materials or introduce alternative real-world examples. Discussions on randomness followed a structured reflection format, but educators had the option to let students design their own experiments. Similarly, while pre- and post-assessments were standardized, teachers can incorporate informal, group-based reflections to deepen student engagement.

The following figure shows the diagram for the curriculum flow and time allocation for each lesson in the curriculum package.

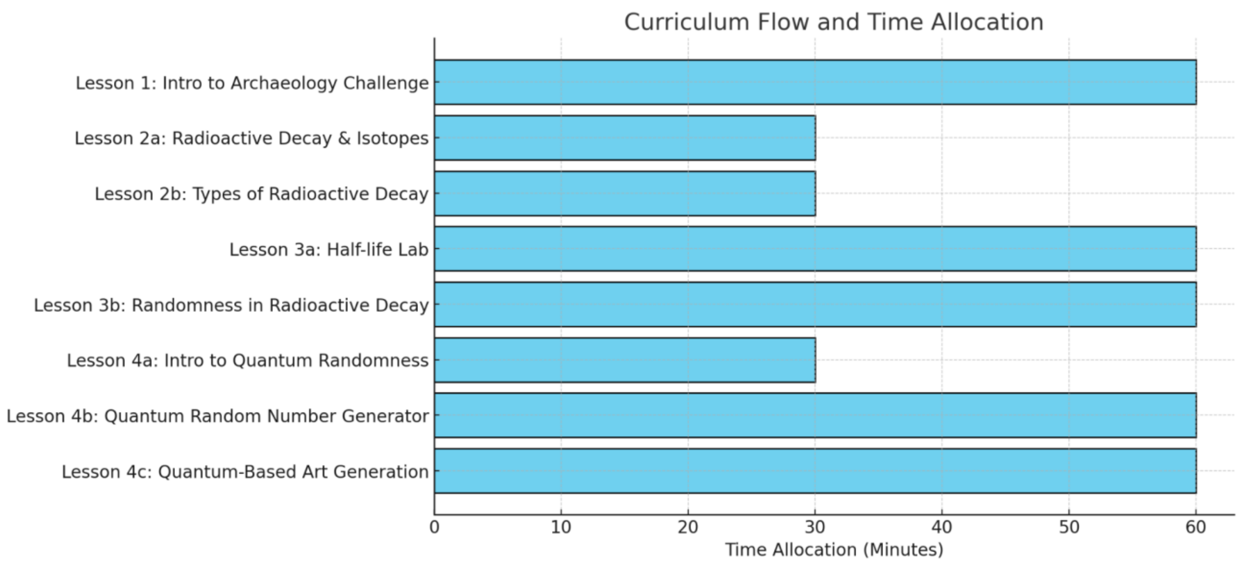


Figure 1: The curriculum flow and time allocation

Teacher Training Program

For recruiting teachers, because we made a middle school science curriculum, we wanted to recruit in-service science teachers. As such, we reached out to local middle schools, asking their school admin to distribute a call for participation. Our call was looking for any in-service middle school science teacher that would be interested in being trained in and implementing our curriculum. The call said teachers would be compensated for participating in curriculum training, and additional, completely optional compensation could be obtained by allowing us to gather student learning data from the curriculum implementation. 10 teachers responded to our call. These 10 teachers were told to attend a curriculum training workshop that we hosted at our institution’s campus.

The workshop took place in the summer of 2022. The workshop was three days long. On the first day, teachers were taught an introduction to quantum mechanics and topics in QISE and had the curriculum presented to them. Presentation of the curriculum included having teachers perform the experiments. The second day continued the presentation of the curriculum with hands-on experience with the curriculum's activities. On the third day, teachers provided feedback on the curriculum and the assessment we made for it. We implemented this feedback and then sent all the teachers a final copy of the curriculum.

Teachers were tasked with following the curriculum unit as presented in the final version. We provided teachers with any materials they needed in order to implement the curriculum. We also visited each teacher's classroom a couple times, while they were implementing the curriculum, in order to verify that they were following it. These 10 teachers taught the curriculum during the academic year 2022-2023 and 2023-2024.

Both academic years, the curriculum was taught as specified in the finalized copy of it sent to the teachers after the workshop held in the summer of 2022. No workshop to train for this curriculum was held in the summer of 2023. Instead, we contacted the same 10 teachers asking if they would consider teaching the curriculum again. They were offered compensation for agreeing to teach again and providing us with student data. All 10 teachers agreed to teach during the academic year 2023-2024.

Research Questions

Having made a curriculum and having trained teachers in it, we were interested in how the curriculum would be received by middle school students; specifically, we were interested in if students found it engaging. Also, we wanted to know if middle school students were able to learn about quantum randomness. As such, we gathered data, over two academic years, aimed at answering the following research questions:

1. Did students find our curriculum engaging?
2. Did students learn the concept of quantum randomness?

Methods

Participants

In both academic years of data collection, there were 10 in-service teachers across seven different middle schools in our local Midwestern U.S. area. There were six male teachers and four female teachers; the average number of years of science teaching experience was 15.

We collected engagement and learning data from 6th, 7th, and 8th grade students. During the academic year 2022-2023, we collected 778 paired responses to the engagement survey and 872 paired responses to the learning assessment. In the academic year 2023-2024, we collected 702 paired responses to the engagement survey and 845 paired responses to the learning assessment.

Data collection

We collected data in the form of a science learning engagement survey and a learning assessment. The surveys were administered, via Qualtrics, in a pre/post-test manner, meaning that before and after the curriculum, the students took the engagement survey and the assessment. The time between data collection instances was between seven or eight days.

To collect engagement data, we used an engagement with science learning survey by [10] and [11]. This survey is a self-evaluation of science learning engagement in four categories: behavioral, emotional, cognitive, and social involvement. The survey used for our study had 25 questions in total: seven questions for the behavioral category and six questions each for the emotional, cognitive, and social involvement categories. The survey questions were all 5-point Likert scale response questions. The scale ranged from zero to five, where zero was “Not at all like me” and five was “Very much like me”. As a check against selecting the same option for each question, we included negatively worded questions that were reverse coded.

To assess if students had learned the concept of quantum randomness, we had the teachers administer an assessment we developed (c.f. Appendix A). The assessment had questions about classical and quantum randomness, but this paper will only focus on the data from the quantum questions (c.f. questions 8-13 in Appendix A).

We constructed assessment items by drawing from the learning goals of each lesson in our curriculum—an approach congruent with the recommendations found in [12]. We also had the help of two field experts when constructing questions. These field experts also gave their approval of the final version of the questions, thus establishing face and construct validity when it comes to field experts. The in-service teachers’ review of these questions during the summer workshop served as another round of establishing face and construct validity; this time the validity was specific to the middle school setting.

Data analysis

To score the engagement data, the score assigned to a response was the Likert level, e.g. if the zero level is “Not at all like me” and a student chose this, then this student’s score for this question is zero.

Scoring the assessment data was more involved. There are multiple-choice and free response questions. The multiple-choice questions were scored dichotomously. The correct answer was assigned a score of two, while incorrect answers received a zero. The free response questions were manually graded according to a rubric that evaluated claim, evidence, and reasoning. This rubric structure came from [13]. The rubric assigned score of either zero, one, or two to each free response question. A zero meant that the response was incorrect and did not present any evidence or reasoning. A one meant that the response was correct in either its claim, evidence, or reasoning but was incorrect with respect to the other categories. A two was a fully correct response, meaning that each category was satisfactorily fulfilled. In the first-year data set, there were three graders. Using Krippendorff’s alpha [14] as the measure of inter-rater reliability, the three graders had an alpha of 0.84, which means good agreement [14]. For the second-year data set, one grader graded the entire data set. This grader was one of the three that graded the first-year data set.

To analyze the paired response score data, we used paired samples, one tailed t-tests. For those concerned about any violations of the assumptions of the t-test these data sets might have, [15]'s empirical work showed that t-tests are robust against violations of its underlying assumptions. Particularly, this robustness holds for a sample size as low as 25 [15]. Given our sample sizes are in the hundreds, we are confident in the robustness of the t-test. Our t-tests were single tailed, because we were looking to see if there was a gain in the measure under question.

Results

Tables 1 and 2 show the results of the paired, single tailed t-tests for the first-year data set of engagement and assessment data. All student data across all grades and schools were lumped into one group.

Table 1

Paired, One-Tailed t-test Results for Engagement Scores (Year 1)

Engagement									
Subscale	**df**	**Pre-survey**		**Post-survey**		**Diff.**	***t***	***p***	**Effect Size**
		Mean	s.d.	Mean	s.d.				
Behavioral	778	2.96	.33	2.98	.36	.019	1.50	.066	-
Emotional	778	2.67	.52	2.78	.44	.107	6.28	<.001	.47
Social	773	2.91	.49	2.99	.48	.078	5.78	<.001	.53
Cognitive	770	2.79	.46	2.90	.44	.105	4.09	<.001	.50

The emotional ([$t(778) = 6.28$], $p < .001$), social ([$t(773) = 5.78$], $p < .001$), and cognitive ([$t(770) = 4.09$], $p < .001$) categories showed a statistically significant difference. The effect sizes were d = .47, d = .53, and d = .50, respectively. These effect sizes are considered moderate [16].

Table 2

Paired, One-Tailed t-test Result for Science Learning Outcomes on Quantum Randomness (Year 1)

Quantum Questions								
df	**Pre-test**		**Post-test**		**Diff.**	***t***	***p***	**Effect Size**
	Mean	s.d.	Mean	s.d.				
872	2.48	2.46	4.96	3.20	2.48	21.30	<.001	0.72

Here, there was statistically significant difference ([$t(872) = 21.30$], $p < .001$) in performance on the quantum randomness questions. The effect size was d = .72. This effect size is considered moderate [16].

Tables 3 and 4 show the results of the paired, single tailed t-tests for the second-year data set of engagement and assessment data. All student data across all grades and schools were lumped into one group.

Table 3

Paired, One-Tailed t-test Results for Engagement Scores (Year 2)

Engagement									
Subscale	**df**	**Pre-survey**		**Post-survey**		**Diff.**	***t***	***p***	**Effect Size**
		Mean	s.d.	Mean	s.d.				
Behavioral	702	2.98	0.42	2.98	0.43	0.001	0.31	0.38	-
Emotional	702	2.75	0.41	2.77	0.41	0.03	1.63	0.05	0.06
Social	702	2.95	0.51	3.00	0.50	0.05	2.72	0.003	0.10
Cognitive	702	2.96	0.47	2.91	0.46	0.05	2.85	1.00	-

The emotional ([$t(702) = 1.63$], $p = .05$) and social ([$t(702) = 2.72$], $p < .01$) categories showed a statistically significant difference. The effect sizes were d = .06 and d = .10, respectively. These effect sizes are considered low [16].

Table 4

Paired, One-Tailed t-test Result for Science Learning Outcomes on Quantum Randomness (Year 2)

Quantum Questions								
df	**Pre-test**		**Post-test**		**Diff.**	***t***	***p***	**Effect Size**
	Mean	s.d.	Mean	s.d.				
845	2.19	2.07	4.37	2.98	2.18	17.72	<.001	0.61

Again, there was a statistically significant difference ([$t(845) = 17.72$], $p < .001$) in performance on the quantum randomness questions. The effect size was d = .61. This effect size is considered moderate [16].

Discussion

The results of this study, conducted over two years, provide valuable insights into the impact of a quantum-infused science curriculum on middle school students' engagement and conceptual understanding. Differences between Year 1 and Year 2 findings highlight variations in engagement subscales and science learning outcomes, which are important to consider for refining curriculum design and implementation strategies.

Research Question 1: Student Engagement

For engagement results, in both years, the behavioral engagement subscale showed minimal changes between pre- and post-surveys, with no statistically significant differences observed in either year. This consistency suggests that while the quantum-infused curriculum may not significantly impact students' observable classroom behaviors, it does not detract from their existing engagement levels. However, the consistently small effect sizes indicate limited influence on this dimension of engagement.

The emotional engagement subscale demonstrated notable differences between the two years. In Year 1, there was a significant improvement, indicating that students developed a stronger emotional connection to the material after exposure to the curriculum. In Year 2, although there was a slight improvement, the effect size was negligible, suggesting a more limited emotional impact. This discrepancy could be attributed to differences in how the curriculum was delivered, variations in teacher expertise, or differences in the student cohort's receptivity.

For social engagement, both years showed significant improvements, but the magnitude differed. The stronger impact in Year 1 suggests that the curriculum was more successful in fostering collaborative discussions and peer interactions during its initial implementation. The reduced effect in Year 2 could indicate a need for enhanced strategies to encourage group-based activities and discussions.

For cognitive engagement, the Year 1 dataset showed that there was a statistically significant difference. This is in contrast to [17], who found that students might find the study of quantum physics not very relevant. So, the result of Year 1 should give readers pause if they are considering that one can generally assume that quantum physics will not capture the interest of middle schoolers, as if our curriculum was able to capture middle schoolers' interest.

Year 2 showed no statistically significant change. Does this then support [17]'s findings? Not necessarily. The absence of improvement in Year 2 could suggest that changes in the curriculum's delivery may have inadvertently reduced its ability to stimulate students' cognitive engagement with quantum concepts. It is also worth considering that since we do not have comprehensive data about past student engagement with science learning, perhaps students found our curriculum content no more interesting than other science content they have learned so far? Overall, we think that quantum physics can capture middle school student cognitive interest, and if there are other curricula where quantum concepts can be infused, one should give it a try.

To summarize, our curriculum had a stronger impact on engagement in Year 1 compared to Year 2. One possible explanation can be differences in how teachers delivered the content across both years. While all participating teachers received the same training and materials, Year 2's implementation may have varied due to differences in classroom conditions, student demographics, or teacher adaptations. Additionally, slight differences in pacing or emphasis on specific concepts could have contributed to the observed variations. Although no formal curricular changes were made, it is possible that Year 1 students benefited from a novelty effect, where the introduction of quantum concepts generated a higher initial level of excitement and engagement.

The lower effect sizes observed in Year 2, particularly for cognitive and emotional engagement, may also suggest a saturation effect, where the curriculum's impact plateaus as teachers become more familiar with the material. Additionally, differences in student cohorts could explain variations in pre- and post-test scores. Further explorations on teacher implementation fidelity and students' background knowledge on quantum concepts could influence the engagement results over multiple years.

Research Question 2: Student Learning

In both years, significant improvements were observed in students' conceptual understanding of quantum randomness, as evidenced by the post-test scores. However, the effect size in Year 1 was larger, indicating a stronger impact on learning outcomes compared to Year 2. This difference may reflect variations in the instructional approach or the grouping of students in Year 2, where all grades and schools were lumped together, potentially introducing heterogeneity that diluted the curriculum's effectiveness. Even so, the result that students meaningfully learned about quantum randomness in both years is an encouraging result that takes its place alongside [4], [5], and [18]. Further, recalling that this curriculum was taught by different teachers at different schools, there is something to be said about how a standardized curriculum with accompanying standardized training can be successful, even when school contexts are different. In sum, our results indicate that students were able to learn of quantum randomness and that this curriculum is potentially scalable.

Limitations

Firstly, there was no control group for this study. As a result, there are no definitive causal links between our curriculum and the results in our data. Even so, given that the curriculum took place and effects were observed, it is reasonable to believe that our curriculum contributed to any observed effects. Secondly, study procedures did not allow us to collect student demographic data. This limits how transferable these findings may be to one's own instructional context.

Conclusion

This paper is a response to calls to bring QISE into K-12 classrooms. We created a quantum infused curriculum that taught quantum randomness, using a pre-existing middle school curriculum about radioactive decay. We used the NGSS and state standards in order to create and sequence the content into a curriculum. We encourage educators and curriculum developers towards a curriculum like ours, because firstly, it does not significantly disrupt pre existing curriculum. We intentionally looked for a place to insert quantum concepts naturally. There are yet other topics where this can be done, such as atomic orbitals or wave mechanics, so this sample curriculum design is by no means a unique circumstance. Second, we encourage others towards our approach in consideration of the learning data we gathered. The results of the science learning engagement data indicated that there was either no significant difference or a positive one. While the effect of the positive difference varied, the main takeaway is that there was no negative difference. So at worst, the students are not any more engaged with science than they were before; their engagement with science learning did not become worse, as one might fear with a subject matter as difficult and confusing as quantum mechanics. Further, the results of the assessment showed that students did grasp the quantum concepts. Even though different teachers taught the curriculum, still, adhering to the standardized plan led to the entire set of middle school students showing a statistically significant difference on the questions assessing understanding of quantum concepts. In sum, we hope that the results of our curriculum will inspire others to design a similar quantum curriculum for middle schoolers as we see potential for it to be extended seamlessly to other topics already taught in middle school and it was seen that a standardized curriculum had positive science learning and content learning effects, even when it was taught in different classrooms.

References

[1] NGSS Lead States, *Next Generation Science Standards: For States, By States*. Washington DC: The National Academies Press, 2013.

[2] National Research Council, “A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas,” The National Academies Press, 2012. doi: 10.17226/13165.

[3] R. Choudhary, A. Foppoli, T. Kaur, D. Blair, R. Burman, and M. Zadnik, “A comparison of short and long Einsteinian physics intervention programmes in middle school,” *Research in Science Education*, vol. 52, no. 1, pp. 305–324, Jul. 2020, doi: 10.1007/s11165-020-09944-8.

[4] R. K. Choudhary, “Measuring the effectiveness of novel learning tools for teaching Einsteinian physics to middle school students with an emphasis on quantum physics,” Ph.D. dissertation, School of Physics, Mathematics and Computing, University of Western Australia, Crawley, Perth, 2021.

[5] A. V. Farris, A. E. Kim, J. Li, and S. Gahosh, “Quantum Computing at the Intersection of Engineering, Technology, Science, and Societal Need: Design of NGSS-aligned Quantum Drug Discovery Lessons for Middle School Students,” in *Middle Atlantic ASEE Section Spring 2021 Conference, Virtual, April 9-10, 2021*.

[6] J. Krajcik, S. Codere, C. Dahsah, R. Bayer, and K. Mun, “Planning instruction to meet the intent of the next generation science standards,” *Journal of Science Teacher Education*, vol. 25, no. 2, pp. 157–175, Mar. 2014, doi: 10.1007/s10972-014-9383-2.

[7] Indiana Department of Education, “2023 Indiana Academic Standards: Grades K-8 Computer Science.” Accessed: Jan. 13, 2025. [Online]. Available: https://media.doe.in.gov/standards/indiana-academic-standards-grades-k-8-computer-science.pdf

[8] K. Juuti and J. Lavonen, “Design-Based Research in Science Education: One step towards Methodology,” *Nordic Studies in Science Education*, vol. 2, no. 2, pp. 54–68, Oct. 2012, doi: 10.5617/nordina.424.

[9] “ANU QRNG – Quantum random numbers.” https://qrng.anu.edu.au/

[10] S. Anwar, M. Menekse, S. Guzey, and L. A. Bryan, “The effectiveness of an integrated STEM curriculum unit on middle school students’ life science learning,” *Journal of Research in Science Teaching*, vol. 59, no. 7, pp. 1204–1234, Feb. 2022, doi: 10.1002/tea.21756.

[11] M.-T. Wang, J. A. Fredricks, F. Ye, T. L. Hofkens, and J. S. Linn, “The Math and Science Engagement Scales: Scale development, validation, and psychometric properties,” *Learning and Instruction*, vol. 43, pp. 16–26, Feb. 2016, doi: 10.1016/j.learninstruc.2016.01.008.

[12] L. A. Shepard, W. R. Penuel, and J. W. Pellegrino, “Classroom assessment principles to support learning and avoid the harms of testing,” *Educational Measurement Issues and Practice*, vol. 37, no. 1, pp. 52–57, Mar. 2018, doi: 10.1111/emip.12195.

[13] K. L. McNeill and D. M. Martin, “Claims, Evidence, and Reasoning: Demystifying Data during a Unit on Simple Machines.,” *Science and Children*, vol. 48, no. 8, pp. 52–56, Apr. 2011, [Online]. Available: https://eric.ed.gov/?id=EJ921138

[14] K. Krippendorff, “Computing Krippendorff’s Alpha-Reliability,” Jan. 25, 2011. https://www.asc.upenn.edu/usr/krippendorff/mwebreliability5.pdf (accessed Jan. 13, 2025).

[15] C. A. Boneau, “The effects of violations of assumptions underlying the T test.,” *Psychological Bulletin*, vol. 57, no. 1, pp. 49–64, 1960.

[16] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*. 2013. doi: 10.4324/9780203771587.

[17] T. S. Moraga-Calderón, H. Buisman, and J. Cramer, “The relevance of learning quantum physics from the perspective of the secondary school student: A case study,” *European Journal of Science and Mathematics Education*, vol. 8, no. 1, pp. 32–50, Jan. 2020, doi: 10.30935/scimath/9545.

[18] D. Franklin, J. Palmer, W. Jang, E. M. Lehman, J. Marckwordt, R. H. Landsberg, A. Muller, and D. Harlow, “Exploring Quantum Reversibility with Young Learners,” in *Proceedings of the 2020 ACM Conference on International Computing Education Research (ICER '20), Dunedin, New Zealand), August 8-13, 2020*. New York: Association for Computing Machinery, 2020. pp. 147–157.

Appendix

The Assessment Instrument

Below is the entire assessment instrument. The correct answer is italicized. Questions 8-13 tested understanding of quantum concepts related to quantum randomness.

1. What is the probability of getting “Tail” when one penny is tossed?

a. 25%

b. 50%

c. 100%

d. 150%

2. Out of 100 students in a school, 20 play tennis, 30 play football, 25 play volleyball, and 25 play basketball. If one student is chosen at random, what is the probability that she or he plays tennis?

a. 100/100

b. 60/100

c. 20/100

d. 25/100

3. When a (six-sided) dice is rolled, what is the probability of getting the number 4?

a. 1/6

b. 4/6

c. ¼

d. 5/6

Please read open-ended questions 4-5 and type/write your responses in the boxes accordingly.

4. Assume that you have a bag of popcorn kernels, and you want to pop these popcorn kernels before your movie night begins.

a. Would it be possible to set up and conduct an experiment that could accurately predict the percentage of popcorn kernels that will pop after a certain time? Why or why not?

Yes. Depending on certain factors (e.g., temperature, the number of kernels in the pan) it would be possible to predict the percentage of the kernels pop.

b. Let’s say you popped different popcorn bags 100 times. Would it be possible to accurately predict when 50% of the popcorn kernels would pop?

Yes. [The answer should be similar to the answer to previous question.] Depending on certain factors (e.g., temperature, the number of kernels in the pan) we can have an estimate when half of the popcorn kernels would pop.

5. Assume that there are 200 Carbon-14 (C-14) atoms that undergo the radioactive decay process in nature. Based on this information, answer the following:

a. How many C-14 atoms remain out of the original 200 atoms after one half-life?
100

b. How many C-14 atoms remain out of the original 200 atoms after two half-lives?
50

c. The C-14 atom has a half-life of approximately 5000 years. How many half-lives should pass in 30,000 years for C-14 atoms? Show your work in the diagram below.
6 half-lives should pass. 30,000 / 5,000 = 6.

<table>
<tr><td>Years/Atom</td><td>200</td><td>100</td><td>50</td><td>25</td><td>12.5</td><td>6.75</td><td>3.375</td></tr>
<tr><td>0</td><td rowspan="2">Half-life 1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5,000</td><td rowspan="2">Half-life 2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>10,000</td><td></td><td rowspan="2">Half-life 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>15,000</td><td></td><td></td><td rowspan="2">Half-life 4</td><td></td><td></td><td></td></tr>
<tr><td>20,000</td><td></td><td></td><td></td><td rowspan="2">Half-life 5</td><td></td><td></td></tr>
<tr><td>25,000</td><td></td><td></td><td></td><td></td><td rowspan="2">Half-life 6</td><td></td></tr>
<tr><td>30,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

d. How many half-lives should pass to have 50 C-14 atoms remaining if the decaying process starts with 200 C-14 atoms? Show your work in the diagram below.

<table>
<tr><td>Years/Atom</td><td>200</td><td>100</td><td>50</td><td>25</td><td>12.5</td><td>6.75</td><td>3.375</td></tr>
<tr><td>0</td><td rowspan="2">Half-life 1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5,000</td><td rowspan="2">Half-life 2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>10,000</td><td></td><td rowspan="2">Half-life 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>15,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

6. Please match the following statements with the corresponding probability choices listed in the table below. Insert X for the matching boxes. The first row shows an example.

<table>
<tr><td rowspan="2">Statement</td><td colspan="3">Probability</td></tr>
<tr><td>100%</td><td>0%</td><td>Between 0%-100%
May or may not happen</td></tr>
<tr><td>Example:
Chances that Pay Less will have more than 500 customers come into the store tomorrow</td><td></td><td></td><td>X</td></tr>
<tr><td>A penny showing Tails or Heads when it is tossed</td><td></td><td></td><td>X</td></tr>
<tr><td>A penny showing Tails when it is tossed</td><td></td><td></td><td>X</td></tr>
</table>

Getting 50 Heads and 50 Tails from 100 pennies at the first toss			*X*
A broken watch correctly shows the time at least once a day	*X*		
A dice rolling 5 at once			*X*
A dice rolling 0 after two throws		*X*	
Putting several dice in a cup and rolling all 6s			*X*

7. Using *The Binary Code Decoder Table* below (also hyperlinked), please answer the following questions:

What is the matching decimal number for the binary number of 1110?
*E*____

What is the matching binary number for the decimal number of 6?
*0110*____

What does the binary number look like for the number string of 5-6-13-11?
0101-0110-1101-1011

What is the matching hexadecimal number for the binary number of 0101?
*5*____

What is the matching decimal number of the hexadecimal number of 8?
*8*____

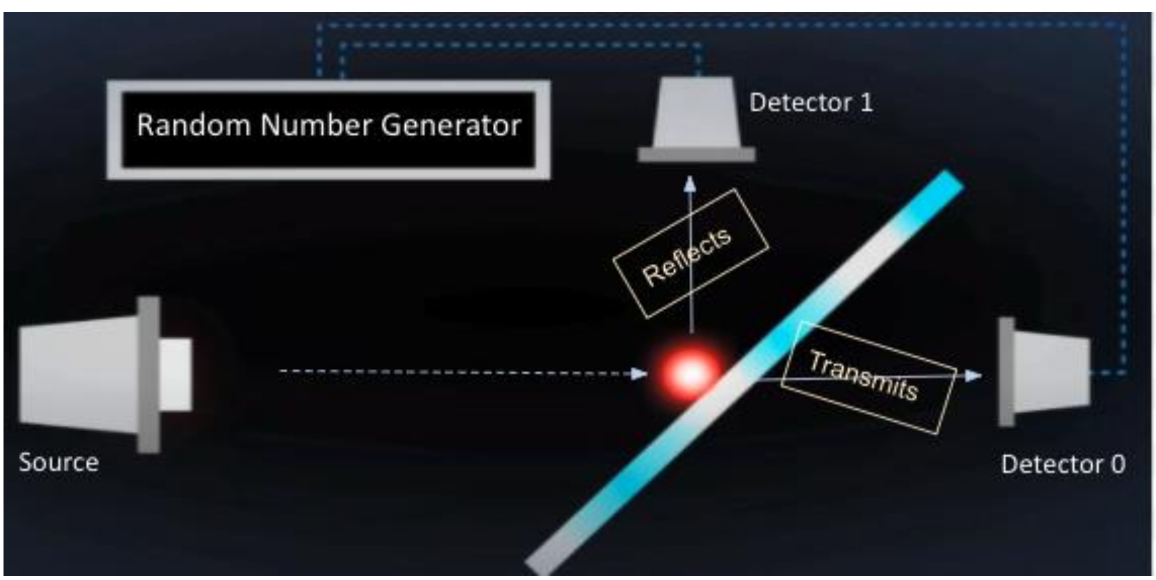
What does the decimal number string look like for the hexadecimal series of 1-3-5-A-C?
1-3-5-10-12

What does the binary number look like for the hexadecimal number series of A-B-C-3-4?
1010-1011-1100-0011-0100

Decimal Numbers	4-bit Binary Number	Hexadecimal Number
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

8. Assume that you are given tennis balls that hit a fence with holes in it (the size of holes is larger than the size of tennis balls). Think about the possibility of tennis balls hitting the fence and bouncing back. Is it random? Why or why not?

It is random. Imagine that you can aim with high precision so that tennis balls should always go through the holes. Quantum randomness can be applied because tennis balls are aimed precisely based on the size and the velocity of the balls.



9. Can we know or predict which detector will receive the optical ball? Why or why not?

No it is random. Once optical ball reflects from the mirror, we can say that Detector 1 creates 1s and send it to the RNG but before optical ball reaches the mirror we may not predict where it will go, it is random. We need to see the measurement. Uncertainty holds until we see measurement results from RNG.

10. What is the possibility of the optical ball (shown in red) will reach Detector 0?

There is a 50% chance.

11. If you are given the binary number 1100 from the random number generator, what would be the probability for each value of getting 0? Why or why not?

There is a 50% chance.

Based on the same experiment please read multiple-choice questions below and select the correct option provided.

12.

a. The detector on the top always receives the optical ball and produces 1.

b. The detector on the right always receives the optical ball and produces 0.

c. The optical ball split in half and both detectors produce numbers at the same time.

d. *We cannot predict which detector will receive the optical ball.*

13. The detector receives multiple optical balls in a row and produces the following message: 11111101111011100111111110…produces more 1s than 0s.

a. The probability of reflection and transmission of the mirror is the same.

b. The probability of reflection and transmission is different.

c. Detectors are not working.

d. More than one optical ball arrives to the mirror.