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Employing Multimedia-based Pedagogy and Primary Literature to Enhance an Introductory Quantum Device Course

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Abstract

This study builds on the initial findings from an NSF-funded project aimed at enhancing the curriculum for Quantum Information Science (QIS). The QIS course modules at the University of Florida have been undergoing iterations of redesign using multimedia-based learning (MBL), dynamic visualization, and simulation-based learning. We applied the European Competence Framework for Quantum Technologies (ECFQT), proposed by Quantum Technology Education, to categorize and measure the skills and competencies gained from an introductory quantum devices course offered in Spring 2024. The (ECFQT) framework comprises seven critical areas, covering foundational concepts and integrating best practices in QIS education. This study addresses the following research questions: (1) RQ-1: In what ways do dynamic visualization and simulation-based slides enhance students' understanding, applying, and retaining the nine key QIS concepts? RQ-2: How does integrating relevant quantum research articles into classroom instruction affect students' learning outcomes and engagement in class? We adopted an interpretive paradigm, which served as a framework to understand and interpret the subjective experiences of individuals. A mixed-method study was conducted to measure the student's learning experiences and evaluate the effectiveness of the redesigned course modules. Our results indicate increased student engagement and improved learning outcomes. Overall, using MBL pedagogy combined with primary research literature was effective and helped students overcome challenges associated with the highly abstract nature of QIS courses.

1 Introduction and Background

Quantum Computing (QC) is a rapidly advancing technology research [1]. It uses quantum mechanics principles, such as superposition and entanglement, to perform calculations much faster than classical computers, which promises to revolutionize society as a major breakthrough in upcoming years [2]. Initially conceptualized by pioneers like Feynman and Benioff, quantum computing has since evolved into a rapidly growing area of research. Advanced nations are adopting strategic approaches to quantum technologies to maintain leadership in advanced technology to strengthen their economies [3]. QC has potential applications in cryptography, artificial intelligence, logistics, Internet of Things (IoT), drug design, and molecular simulations [4–7]. The US national agencies such as the NSA, DOD, DOE, NIST, NSF, NASA, and leading companies such as Microsoft, Google, Intel, IBM, Lockheed Martin, and others are investing heavily to drive quantum technology development [4]. With these substantial investments, the demand for a quantum-skilled workforce is rapidly increasing [8]. However, there is a notable shortage of skilled professionals in quantum computing, underscoring the urgent need to train and prepare new generations of engineers, scientists, and programmers to tackle real-world challenges and bring state of the art problem solving skills in the quantum field [9].

Quantum computing faces significant entry barriers due to the specialized expertise it demands and the limited availability of skilled professionals in this field [2]. This rising demand for QC specialists has exposed substantial gaps between the growing number of job opportunities and the relatively small pool of qualified graduates entering the workforce each year [10]. This challenge is made more difficult by the inherent complexity of the domain, which requires a strong foundation in mathematics, quantum physics, and mechanics [11]. As a result, only students with a strong academic background and a genuine interest in the subject often pursue this field. To address this shortage, the first step in addressing this quantum divide is to improve quantum computing education by employing Multimedia Based Learning (MBL) techniques to lower the cognitive barrier and make the subject more accessible to a broader range of learners. The Department of Electrical and Computer Engineering (ECE) at the University of Florida has redesigned its EEE 5934 Introductory Quantum Hardware Devices course to meet the learning needs of both graduate and undergraduate students. This course aims to provide students with a strong foundation and advanced skills in quantum hardware. The curriculum is centered around the nine core concepts of Quantum Information Science (QIS) [3] and incorporates innovative teaching methods through multi-media tools, such as visualization and simulations, to enhance learning and engagement. Moreover, the course modules are aligned with research articles and Nobel laureate lectures, offering valuable resources to support students who may lack prior knowledge in the quantum physics and mechanics domains. This paper shares insights from the second year of the INQUIRE project, focusing on undergraduate QIST education.

2 Motivation

QIS is already facing significant challenges in workforce development, exacerbated by factors that impede effective learning. These include, but are not limited to, the structure and organization of the curriculum, the learning environment, assessment methods, feedback quality, and the need for students to engage with tools and concepts outside their existing expertise and comfort zone [3, 12–15].
This study examines students' subjective experiences and competency development in the EEE 5934 course that integrates multimedia-based learning (MBL), the European Competence Framework for Quantum Technology (ECFQT), and curated research latest research articles in the syllabus. Employing a mixed-methods approach grounded in a pragmatic and interpretive paradigm, the study combines quantitative and qualitative data to explore how students interpret and engage with these instructional strategies.
The pragmatic approach supports using diverse methods to evaluate learning outcomes, while the interpretive paradigm focuses on understanding students' experiences with MBL and assessments and integrating domain-specific research articles. By evaluating the impact of dynamic visualizations, simulation-based slides, and research integration, this study aims to inform curriculum design and enhance competency development in quantum technologies. Specifically, this study addresses the following two research questions:
RQ-1: In what ways do dynamic visualization and simulation-based slides enhance students' understanding, applying, and retaining the nine key QIS concepts? RQ-2:How does integrating relevant quantum research articles into classroom instruction affect students' learning outcomes and engagement in class?

3 Methodology

This study adopted a mixed-methods design, integrating qualitative and quantitative data to evaluate participants' learning outcomes and experiences in the EEE 5934 course, as shown in Figure 1. Data were collected from interviews, surveys, and classroom observations. Interviews with instructors and students provided detailed insights into teaching methods, learning challenges, and the inclusion of research articles. Baseline and exit surveys assessed participants' prior knowledge, learning progress, and overall feedback. Classroom observations captured real-time engagement and instructional practices.

The study evaluated the prior knowledge of the participants about the nine key QIS concepts, analyzed how the course materials and teaching strategies facilitated learning, and measured participants' understanding of these concepts of the participants after the course was completed. The collected qualitative and quantitative data were systematically analyzed to derive insights into course effectiveness, emphasizing areas for improvement and identifying successful practices that enhanced learning outcomes and engagement.

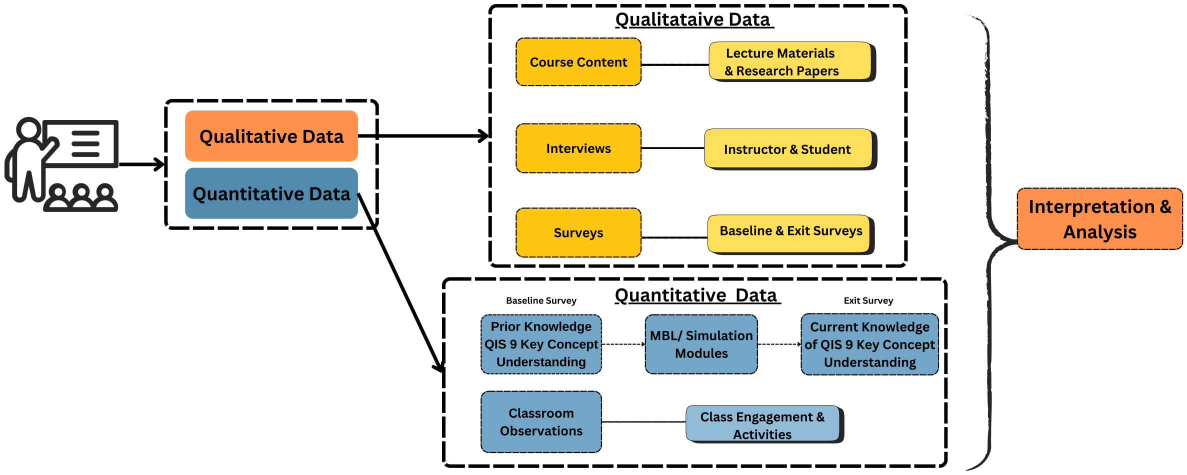

Figure 1: Mixed-Methods Design for Evaluating the EEE 5934 Course Outcomes

4 Pedagogical Approach

Modern pedagogy is primarily founded on Vygotsky's constructivist learning theory (1978). A key implication of constructivism for educators is that learners actively build their understanding, knowledge, and skills through interactions with their environment, including significant engagement with their social surroundings [16]. Such principles have significant implications for designing the QIS curriculum, particularly fostering an environment where students actively construct their learning [17]. Aligned with this philosophy, the instructor implemented Inquiry-Based Learning (IBL). IBL encourages interactive learning driven by questioning and exploration, mirroring the scientific process. There are many models of Inquiry-based learning [18]. The course utilized the 5E Cycle (Engagement, Exploration, Explanation, Elaboration, and Evaluation) teaching approach, as also recommended in [19]. During the Engagement phase, students discuss their pre-noted questions and observations in the research articles they were assigned to read before class. In the exploration phase, students independently investigate concepts by maintaining a list of questions. In the Explanation phase, the instructor uses the lecture materials to clarify key concepts and address the challenges identified during the exploration phase. The Elaboration phase extends learning by introducing advanced problems and case studies in the lectures. Finally, in the Evaluation phase, comprehension was assessed by reviewing the homework sets, reflective discussions, and final paper presentation. Regardless, this structured approach ensured that students engaged deeply with the material, developed critical thinking skills, and connected theory with practical application in QIS.

5 Course Structure

This course was taught in the Spring 2024 semester, during which students attended three lectures per week, each of 50 minutes duration. The study participants in EEE 5934 included 10 students, 7 enrolled in the course and 3 auditing, all of whom participated in every course activity. As shown in Table 1, the course syllabus outlines the structured progression of topics in six modules, ensuring alignment with the nine key concepts of Quantum Information Science (QIS). This design integrates foundational learning, advanced concepts, and practical applications to provide a comprehensive learning experience.

#Weeks	Module	Topics	Description
1	Physics Foundation	History of the First Quantum Revolution	• Reviewing the history of the first quantum revolution. • Recapping the fundamentals in solid-state physics and quantum mechanics
2	Physics Foundation	Impact of the First Quantum Revolution	•Demonstrating how quantum mechanics leads to the major technological breakthroughs • Case study with lasers and transistors, etc.
3	Quantum Computing	Introduction to Quantum Computing	•Introducing the basic concepts of quantum computing • Comparison with classical computing
4	Quantum Computing	Key Milestones in Quantum Computing	•Reviewing the development of quantum computing • Deriving road map and Figures of Merit (FoM)
5	Quantum Computing	Building Block of Quantum Computer (I)	•Introducing hardware implementation based on atoms/ions/molecules, superconducting junctions
6	Quantum Computing	Superconducting technology for quantum computing	•Introducing hardware implementation based on quantum dots, solid-state defect centers, topological insulators, and others
7	Quantum Computing	Semiconductor technology for quantum computing	•Introducing the overall architecture of quantum computer and the concept of error correction
8	-	Mid-Project	
9	Quantum Communi-cation	Introduction to Quantum Communication	•Introducing the basic concepts of quantum communication • Comparing with current optical communication
10	Quantum Communi-cation	Key Milestone in Quantum Communication	•Reviewing the development of quantum communication • Deriving road map and figures of merit (FoM)
11	Quantum Communi-cation	Quantum Network Architecture and Implementation	•Introducing the overall architecture of quantum network and communication protocols
12	Quantum Sensing	Introduction to Quantum Sensing	•Introducing the concept of quantum sensing • Case study of optically detected magnetic resonance and quantum N/MEMS sensing
13	Quantum Simulation	Introduction to Quantum Simulations	•Introducing the concept of quantum simulation • Experiencing IBM-Q
14	Perspective and Future Applica-tions	Open discussion on Perspective and Future Application of QIST	•Open discussion and final project presentation
15	Final Paper	Final Presentation and Final Paper Due	•Presentations

Table 1: EEE 5934 Course Syllabus

5.1 Lecture Content

The course instructor has designed the slides using multimedia-based learning (MBL) techniques to design lecture slides aimed at reducing the cognitive load associated with complex quantum concepts. This approach enhanced students' understanding and engagement. Nobel Laureate lectures and curated online resources were incorporated to provide foundational support for students. The list of lectures is depicted in Table 2.

The lecture slides were designed to preserve the academic rigor of the topic/module while integrating animation, dynamic visualization, and simulations to enhance students' comprehension of 9 Key QIS concepts. Figure 2 and Figure 3 present two exemplars from the lecture materials, demonstrating the role of interactive visual elements in fostering conceptual clarity and improving knowledge retention.

The conceptual framework of oscillations and vibrational modes was introduced incrementally, starting from one-dimensional (1D) systems and progressing to three-dimensional (3D) systems. In studying oscillatory modes across dimensions Figure 2(a), the Boltzmann distribution provides a statistical framework for understanding the energy distribution among vibrational states. This foundation is crucial for linking classical vibrational principles to advanced topics like thermodynamics and quantum behavior.

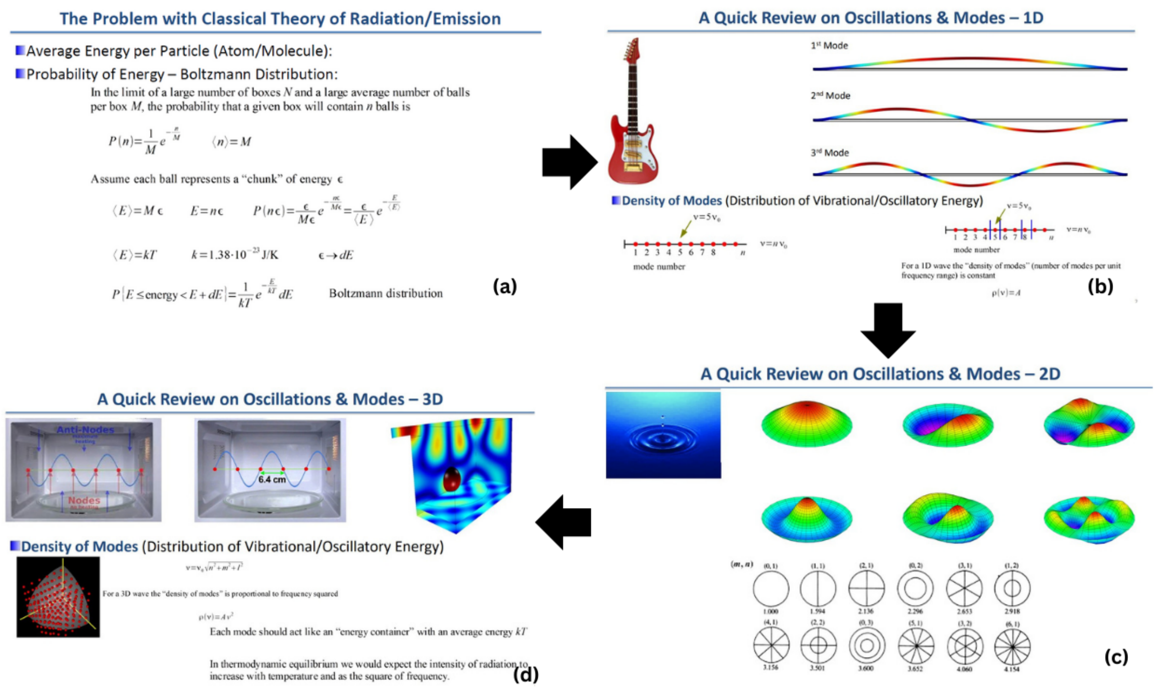

Figure 2: Visualization of Foundational Knowledge: Demonstrating the Transition from Classical Theory to Quantum Concepts Using MBL Tools Across 1D, 2D, and 3D Oscillatory Modes

As illustrated in Figure 2 (b), the instructor began with a 1D example, using the vibrational modes of a guitar string to demonstrate the fundamental principles of oscillatory behavior. This 1-D visualization enabled students to understand the sequential progression from the fundamental mode (1st mode) to higher-order modes (2nd and 3rd modes) while highlighting the distribution of vibrational energy and the relationship between mode number and frequency. Building on this foundation, the instructor transitioned to 2D oscillatory systems, as depicted in Figure 2 (c). The discussion focused on the vibrational patterns of a circular membrane, such as a drumhead, where both radial and angular nodes contribute to the complexity of the observed modes. This step demonstrated how the oscillatory behavior in a planar system differs from that in a linear system.

The progression culminated with 3D oscillatory systems, as shown in Figure 2 (d). Examples such as standing wave patterns in a microwave cavity and resonance modes in three-dimensional structures were used through animations to illustrate the increased complexity of vibrational modes in three-dimensional space. The distribution of vibrational energy in these systems, characterized by the density of modes being proportional to the square of the frequency, was also discussed. This final step connected the theoretical framework of oscillations to practical applications, reinforcing the importance of understanding oscillatory behavior across different dimensions.

Similarly, to understand the Schrodinger equation in the context of the hydrogen atom, the instructor demonstrated mathematical calculation, followed by 2D and 3D visualization along with simulations of quantum state for n. Students were then directed to use the Paul Falstad simulator applet to interactively explore electron wave functions, further enhancing their understanding of the quantum states as illustrated in Figure 3.

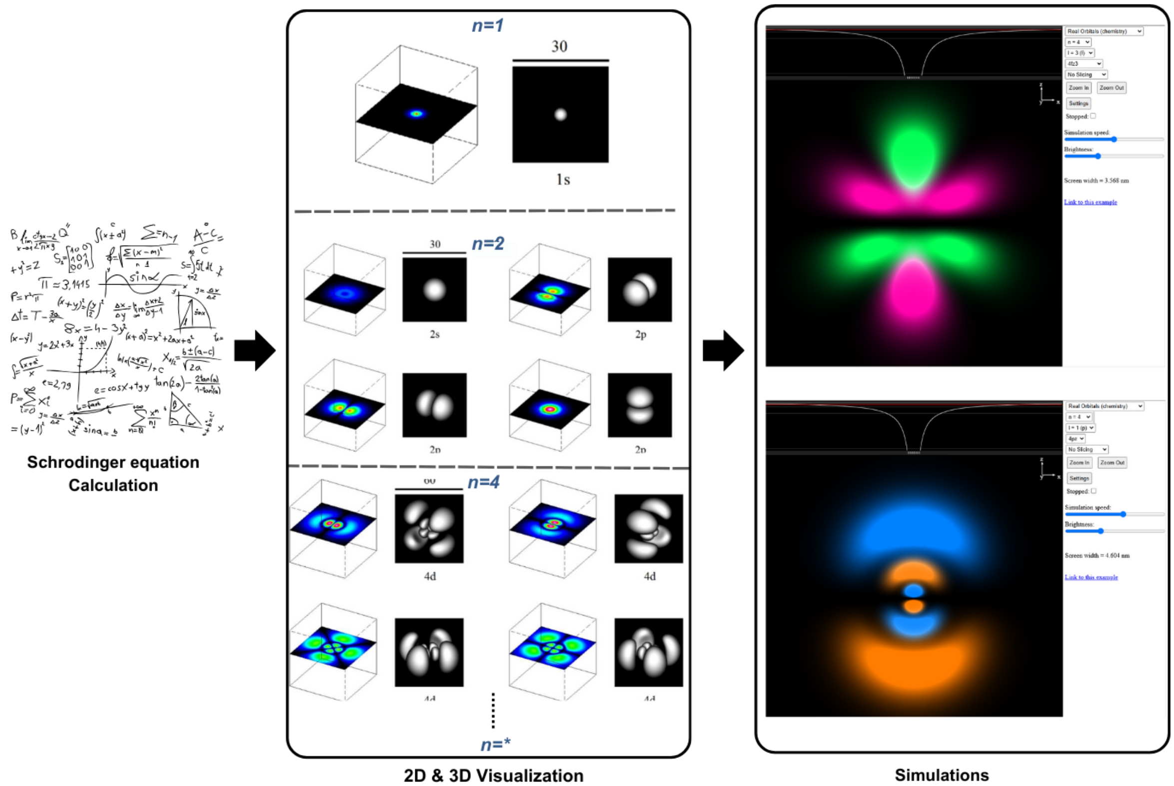

Figure 3: Visualization of Hydrogen Atom Orbitals: From Schrödinger Equation Calculations to 2D & 3D Representations and Simulations for Enhanced Conceptual Understanding

Table 2: List of Nobel Laureates and National Reports as additional Resources employed in EEE 5934 Course

Authors	**Lectures titles with Publishing Year**
Reports	Opportunities for Basic Research for Next-Generation Quantum Systems [20] Quantum Networks for Open Science Workshop[21]
Alain Aspect, John Clauser and Anton Zeilinger	Nobel Report: For Experiments with entangled photons, establishing the violation of bell inequalities and pioneering quantum information science (2022)
Serge Haroche	Nobel Report: Controlling Photons in a Box and Exploring the Quantum to Classical Boundary (2012)
Steven Chu	Nobel Report: The Manipulation of Neutral Particles (1997)
Wolfgang Paul	Nobel Report: Electromagnetic Traps for Charged and Neutral Particles (1987)

5.2 Course Assessments

The course assessment comprised a midterm and a final presentation. This is different from the previous iterations of the course; their homework and quizzes were assigned on a regular basis. The revised assessment challenges students to apply, analyze, and evaluate the information they have learned. This method was intended to develop critical thinking and practical application skills, preparing students for higher-level cognitive tasks.

5.3 Competency-Based Activity Mapping

The rapid expansion of Quantum Technologies (QT) has increased demand for specialized workforce. Several national and international efforts have been initiated to address the quantum skill gap and ensure a pipeline of qualified professionals [22]. The European Competency Framework for Quantum Technologies (ECFQT) was developed under the European Quantum Flagship program [23]. The ECFQT was developed to identify and categorize the key competencies, knowledge, and skills needed for the future quantum workforce. It provides a multi-level structured approach to designing quantum educational programs across Europe. The framework is organized into three main categories: theoretical background, practical background, and application [24]. To measure student outcomes in EEE 5934, we mapped the course activities onto the (ECFQT). The analysis gave us the means to ascertain where students would be expected to develop specific core competencies in quantum education. We integrated theoretical and practical components of quantum education through structured mapping of course activities to relevant domains within the framework. Figure 4 highlights two overarching categories, Theoretical Quantum Background, and Quantum Technologies, which encompass several domains. Each activity addresses specific aspects of the domain and its subdomains, providing structured support for students to progressively develop expertise in different competencies. However, no activities were associated with Domains 6 and 7.

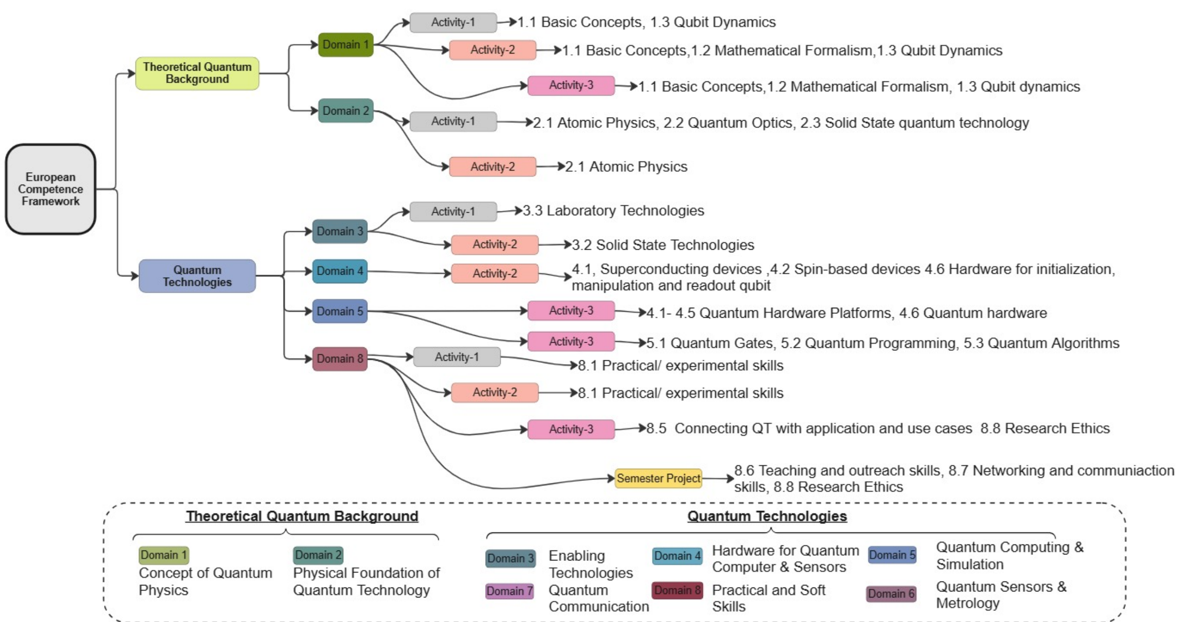

Figure 4: European Competency Framework for Quantum Technologies Activity Mapping

6 Data Collection

The data collection strategy employed in this study is illustrated in Figure 5, reflecting the systematic approach used to gather qualitative and quantitative data.

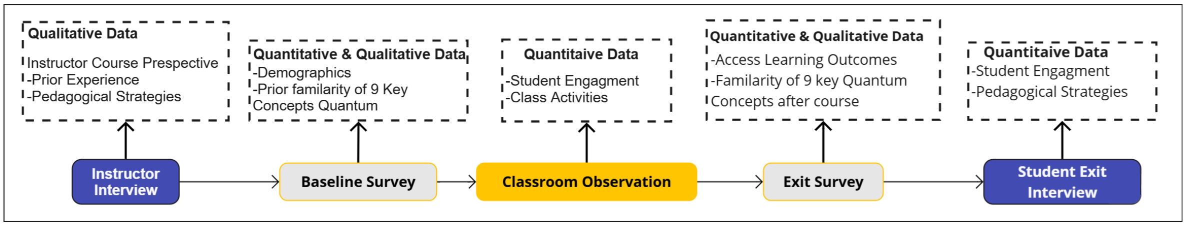

Figure 5: Data Collection Phases

6.1 Interviews

At the start of the study, a 45-minute Zoom interview was conducted with the course instructor, who has been teaching this course since 2020, to explore their observations on students' challenges with the course material. The discussion focused on identifying specific areas where students commonly struggled and examining the instructional strategies employed to enhance comprehension and facilitate learning. The instructor also reflected on their teaching practices, discussing strategies employed to facilitate learning and improve student comprehension. Upon course completion, student exit interviews were conducted to gather participant feedback. These interviews provided valuable reflections on the course structure, the effectiveness of learning resources, and insights into how students navigated difficulties throughout the course. The interviews offered a detailed perspective on the course from both an instructional and a student point of view.

6.2 Survey

The study employed two previously developed survey instruments for the project [11], administered as baseline and exit surveys through Qualtrics to capture participants' experiences.
The baseline survey, conducted in the first week of the semester, assessed participants' prior exposure, familiarity, and understanding of quantum concepts before enrolling in the EEE 5934 course. Participants provided demographic information and details of their previous exposure to quantum topics through various academic and learning platforms.
A key survey question asked, *"How familiar are you with the basic nine key concepts of quantum?"* Participants reviewed the concepts via a provided link before answering. Familiarity levels ranged from "Extremely familiar," "Very familiar," "Moderately familiar," "Slightly familiar," or "Not familiar at all." Logical branching guided participants to tailored follow-up questions based on responses. Those with moderate to high familiarity rated their understanding of nine key concepts on a 1-5 scale, where 1 indicated minimal understanding, and 5 represented a thorough understanding of nine quantum concepts. while others answered questions about general confidence, programming skills, preferred learning styles, and topics that interest them in the quantum field.

The exit survey evaluated participants' learning outcomes, their understanding of the nine quantum concepts, and their perceptions of the course. It assessed various aspects of the course structure, including design, pacing, difficulty, and workload, to ensure a balance between challenge and manageability. The effectiveness of the instruction was also examined, focusing on the clarity of the teaching and the use of innovative strategies. A significant part of the survey focused on the effectiveness of simulated and dynamic visualization slides in enhancing students' comprehension of QIS concepts. A Likert-scale questionnaire was used to measure the impact of these instructional tools, allowing participants to express their level of agreement with statements related to their learning experiences, ranging from" strongly disagree" to" strongly agree." The participants also reflected on the most and least engaging aspects and rated students, analyzed the associated reading, and compiled a glossary of questions from their reading.

6.3 Classroom Observations

To investigate the teaching practices and student engagement patterns in this course, we utilized the Classroom Observation Protocol for Undergraduate STEM (COPUS)[25]. This framework was selected for its objective, structured, and non-evaluative approach to characterizing classroom activities, enabling us to assess the effectiveness of pedagogical strategies in this quantum course. As part of the instructional design, students were assigned specific research articles relevant to each lecture topics. These reading assignments aimed to establish foundational knowledge and encourage critical engagement with the course material. Students analyzed the associated reading and compiled a glossary of questions from their reading. These questions helped them develop foundational knowledge, enabling them to engage in in-depth class discussions on the topic. Observations were conducted over six sessions of a graduate-level QIS course, with activities recorded at two-minute intervals using the standardized COPUS coding scheme. The data was analyzed to identify the proportion of class time spent on traditional lecturing versus active learning approaches, such as group discussions, problem-solving, and glossary review. Results were visualized using bar charts and heat maps to highlight activity patterns.

7 Quantitative Data Analysis

7.1 Surveys

The analysis compares participants' self-reported understanding of nine quantum concepts across two survey points: the baseline survey (n = 10) at the beginning and the exit survey (n = 2) at the end of the semester. The baseline survey used a logical flow to direct participants based on their familiarity with nine key quantum concepts. Participants first reviewed the concepts through a provided link and then responded to a question about their familiarity. If the participants selected " Moderate Familiarity, Very Familiar, or Extremely Familiar, they were directed to Question 11, where they rated their understanding of each concept using a 5-point Likert scale. If participants selected not familiar, they were directed to Question 12, which was tailored for those with fewer familiarities.

Baseline Survey Results In the initial survey, n=10 participants participated; however, only 7 out of 12 met the familiarity threshold of Quantum Information Science (QIS) in Question 10 and proceeded to rate their understanding of the nine quantum concepts. Among these participants, Quantum State (M = 3.29, SD = 1.28) and Quantum bit or Qubit (M = 3.14, SD = 0.83) received the highest ratings, suggesting moderate familiarity with these concepts. Conversely, Quantum Sensing (M = 1.71, SD = 0.45) and Quantum Communication (M = 2.29, SD = 0.45) were rated the lowest, indicating a limited understanding of these topics, as shown in Table 3.

Table 3: Baseline Ratings of Participants' Understanding of Nine Quantum Concepts ($n = 7$)

Quantum Concept	Min	Max	Mean (M)	Median	SD	Variance	Sum
Quantum Information Science	1.0	3.0	2.71	3.00	0.70	0.49	19.00
Quantum State	1.0	5.0	3.29	3.00	1.28	1.63	23.00
Quantum Measurement	2.0	5.0	2.71	2.00	1.03	1.06	19.00
Quantum bit or Qubit	2.0	5.0	3.14	3.00	0.83	0.69	22.00
Entanglement	2.0	5.0	2.86	3.00	0.99	0.98	20.00
Quantum Information Application	1.0	3.0	2.00	2.00	0.53	0.29	14.00
Quantum Computers	2.0	3.0	2.43	2.00	0.49	0.24	17.00
Quantum Communication	2.0	3.0	2.29	2.00	0.45	0.20	16.00
Quantum Sensing	1.0	2.0	1.71	2.00	0.45	0.20	12.00

Since only two participants, P2 and P8, participated in the exit survey, we present their prior understanding of the nine QIS concepts in Table 4.

Table 4: P2 & P8 Prior Understanding of 9 QIS Concepts

Quantum Concept	**Min**	**Max**	**Mean (M)**	**Median**	**SD**	**Variance**	**Sum**
Quantum Information Science	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum State	1.0	1.0	1.00	1.00	0.00	0.00	2.00
Quantum Measurement	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum bit or Qubit	2.0	2.0	2.00	2.00	0.00	0.00	4.00
Entanglement	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum Information Application	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum Computers	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum Communication	1.0	2.0	1.50	1.50	0.50	0.25	3.00
Quantum Sensing	1.0	2.0	1.50	1.50	0.50	0.25	3.00

Exit Survey Results To evaluate the effectiveness of the course, all participants (n = 10) were invited via email to share their reflections and complete an exit survey. Despite the outreach, only two participants, P2 and P8, responded and completed the survey. Table 5 summarizes P2 and P8's self-reported understanding of nine key quantum concepts after the course. The data were collected using a standardized rating scale, with the table showcasing statistical metrics such as the mean, median, minimum, maximum, standard deviation, and variance for each concept. This comprehensive overview offered valuable insights into participants' strengths and areas requiring further development, facilitating targeted enhancements in future course iterations. Additionally, both participants strongly agreed that using of simulation and dynamic visualization slides facilitated their understanding of QIS concepts.

Table 5: (P2) &(P8) After intervention understanding of 9 QIS concepts

Quantum Concept	**Min**	**Max**	**Mean (M)**	**Median**	**SD**	**Variance**	**Sum**
Quantum Information Science	4.0	4.0	4.00	4.00	0.00	0.00	8.00
Quantum State	4.0	4.0	4.00	4.00	0.00	0.00	8.00
Quantum Measurement	4.0	4.0	4.00	4.00	0.00	0.00	8.00
Quantum bit or Qubit	4.0	5.0	4.00	4.50	0.50	0.25	9.00
Entanglement	3.0	4.0	3.50	3.50	0.50	0.25	7.00
Quantum Information Application	3.0	4.0	3.50	3.50	0.50	0.25	7.00
Quantum Computers	2.0	4.0	3.00	3.00	1.00	1.00	6.00
Quantum Communication	3.0	4.0	3.50	3.50	0.50	0.25	7.00
Quantum Sensing	3.0	4.0	3.50	3.50	0.50	0.25	7.00

7.2 Comparative Analysis

The comparison of mean scores between the baseline and exit surveys of P2 and P8 reveals improvement in participants' understanding of all nine QIS concepts. In the baseline survey, participants reported limited familiarity with most concepts, with a mean score ranging from 1.00 to 2.00. Quantum bit or Qubit received the highest mean score (2.00), indicating slightly better initial understanding, while other concepts were rated lowest.

In contrast, the exit survey showed substantial growth in understanding across all concepts. The mean score for most concepts reached 3.50 or above, with Quantum Information Science, Quantum State, and Quantum Measurement achieving perfect scores (M = 4.00). Quantum bit or Qubit demonstrated the highest overall improvement, with a mean score of 4.50, reflecting strong familiarity after the intervention. Additionally, Entanglement, Quantum Information Application, Quantum Communication, and Quantum Sensing showed notable increases in mean scores (M = 3.50). The results demonstrate the instructional intervention's effectiveness in enhancing participants' understanding of quantum concepts. However, Quantum Computers scored lower (M = 3.00) in the exit survey, suggesting the need for additional focus on this topic. The heat map of the baseline vs. exit survey is illustrated in Figure 6. The mean understanding scores of nine QIS key concepts of P2 and P8 were improved from their baseline survey. Darker shades on the heat map represent higher scores, showing improvements across all concepts.

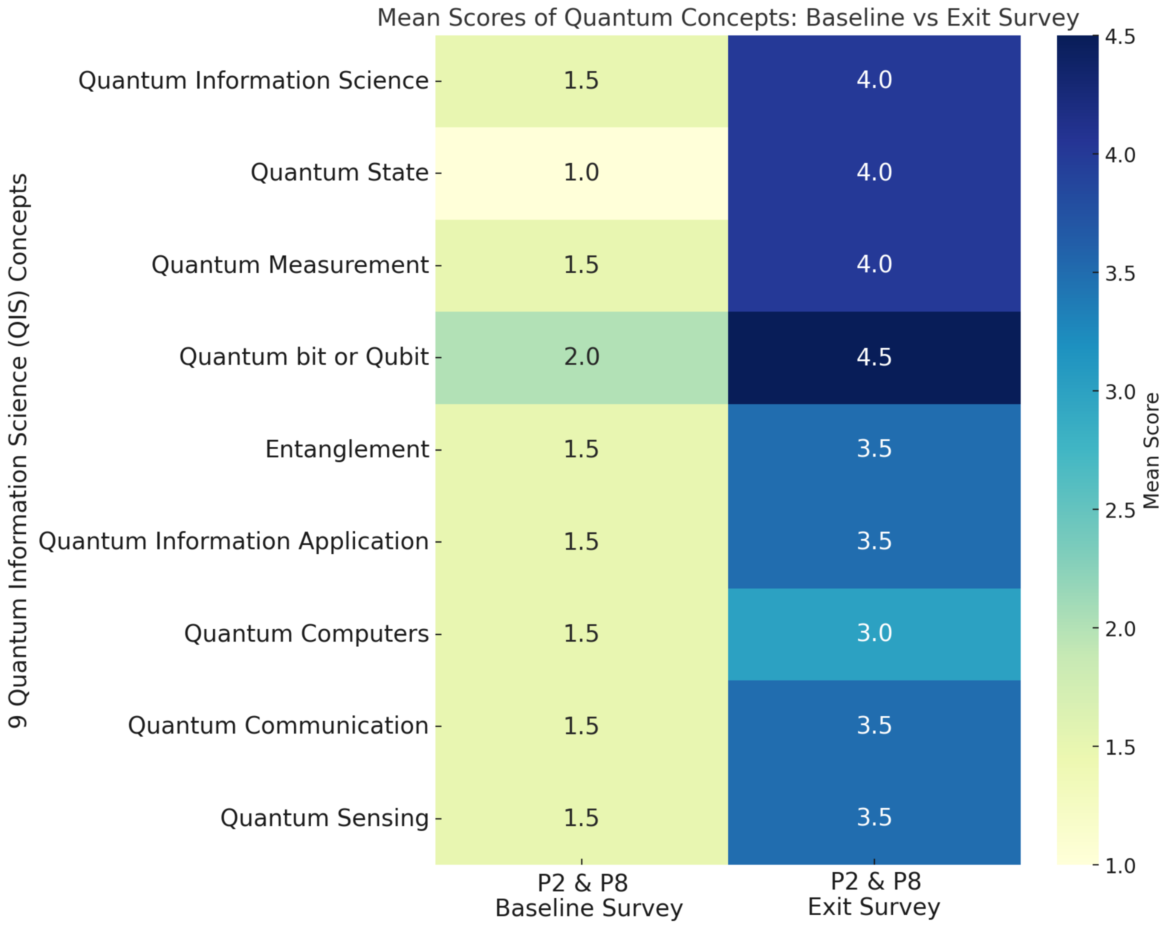

Figure 6: Heat map Comparing Mean Understanding Scores Across Modules: Baseline vs Exit Surveys

7.3 Classroom Observations Findings

The findings emphasize the effect on student engagement, which increased significantly, as depicted in Figure 7. The instructor utilized research articles to establish the foundational knowledge of the day's topic. The class began with a discussion, as evidenced by high levels of student activity in the figure. These activities included asking questions (48%), answering questions posed by the instructor (38%), and participating in whole-class discussions (31%). These interactive activities demonstrated that students actively articulated their understanding and clarified concepts from the provided resources. Cognitive engagement is further supported by substantial involvement in thinking (50%) and predicting animation (50%). Although listening (62%) accounted for the largest portion of students' activity, the focus on discussion and analysis highlights the instructor's effort to promote active learning. Collaborative activities, such as working in groups (8%), were present but minimal. Adopting this strategy has improved student engagement from the previous iteration of the course [11].

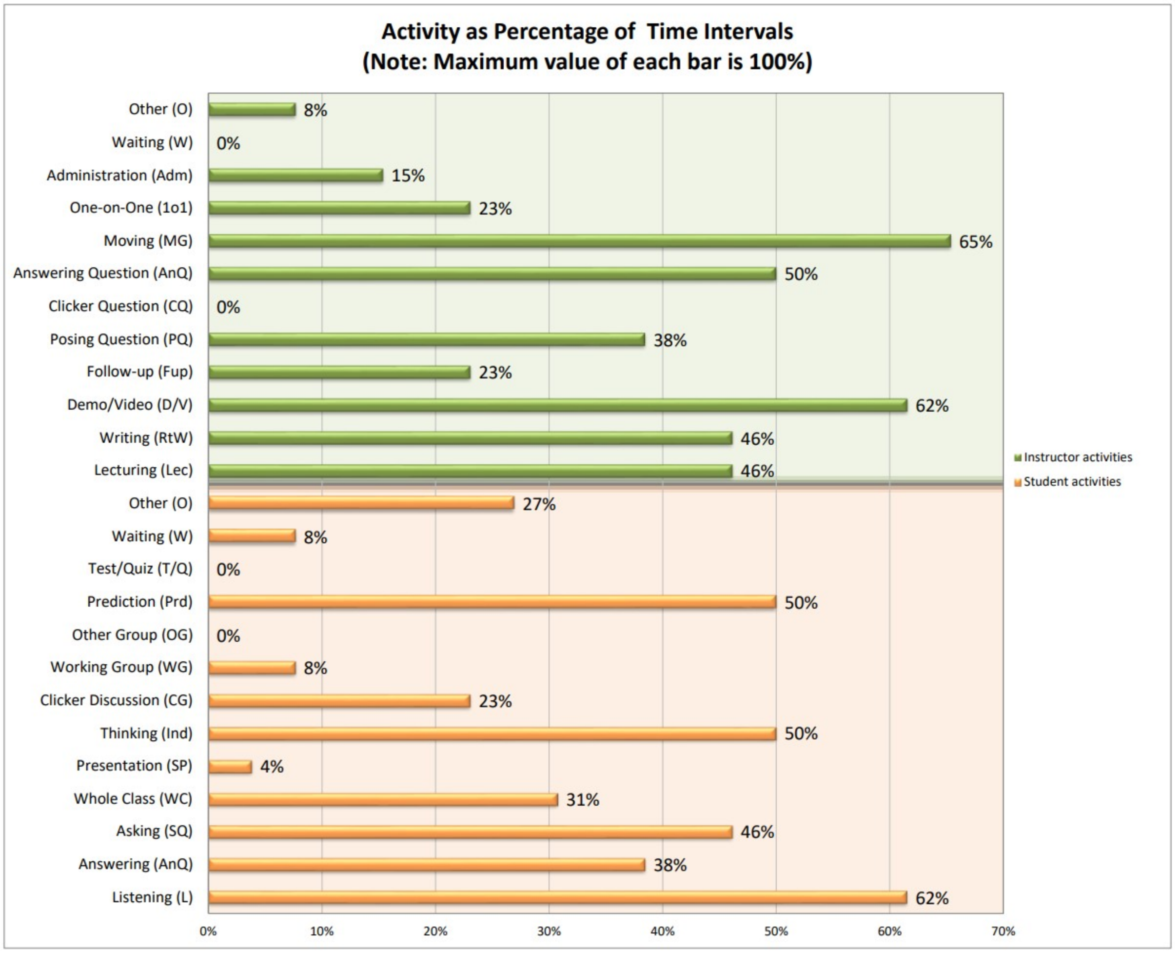

Figure 7: Activity as Percentage of Time Interval

7.4 Qualitative Data Analysis

Following the exit survey, both participants (P2 and P8) were invited to individual 45-minute Zoom interviews to provide deeper insights into their course experiences. The interview data were transcribed and analyzed using MAXQDA software, ensuring a comprehensive and systematic approach to qualitative analysis. The coding process was conducted in two cycles by independent coders. During the first cycle, the coders identified patterns and themes while recording reflections to capture initial impressions and emerging questions. These insights informed the development of a detailed code book. In the second cycle, the coders applied the code book to reassess the data and ensure consistency in their analyses. The inter-coder reliability was evaluated using Cohen's Kappa, yielding a score of 0.80, which reflects a high level of agreement and consistency.

Five overarching themes emerged from the analysis: (1) student background and preparation, (2) course materials, (3) learning engagement, (4) assessments and outcomes, and (5) teaching methodology.

Theme 1: Student Background and Preparedness

The course required prior knowledge of quantum mechanics and quantum physics, creating challenges for most students. The instructor expressed the need to bridge a lack of prior knowledge in quantum mechanics and quantum physics.

- *"Students usually find abstract concepts difficult to grasp. In particular, topics such as entanglement and superposition are inherently difficult." [Instructor]*

Upon being asked about why these concepts are difficult to grasp, the instructor responded that

- *"These topics require foundational knowledge of [quantum mechanics and physics]. Without the foundation, it becomes difficult for the students to follow along." [Instructor]*

Participants also expressed the need for foundational courses to bridge knowledge gaps and enable more meaningful engagement with course content.

- *"The course gave me an idea about what I had studied before in quantum mechanics... But for someone who hasn't taken any courses related to quantum mechanics, I think they would face a lot of difficulties... Personally, I struggle to understand the entanglement concept" [P2]*
- *"In order to read a research paper, they mostly do not explain everything. I just have to keep looking up this term, that term... It would be much more efficient for me if I had done a [foundational] course before... I struggled with many concepts, but... superconducting qubit was one of them" [P8]*

Theme 2: Course Materials

The course materials, including dynamic and simulation-based slides, Nobel laureate lectures, national reports, and research articles, played a crucial role in facilitating student learning without compromising the rigor of the course. The instructor emphasized the importance of incorporating Nobel laureate lectures and topic-oriented research articles as scaffolding tools to enhance student engagement.

- *"In this iteration of the course, we have redesigned the course to enhance conceptual understanding while maintaining its academic rigor. Our approach integrates evidence-based instructional strategies, including the use of curated resources such as Nobel Laureate Lectures, and topic-wise research articles to scaffold foundational knowledge."[Instructor]*

  He further emphasized that the inclusion of these types of additional resources helps students to understand the real application of the domain.

- *"These lectures also serve as a bridge between theoretical concepts and real-world application, making abstract ideas more tangible for students."[Instructor]*

  When asked about what strategies were implemented to reduce the cognitive load while simplifying the quantum concepts, and maintaining academic rigor, the instructor responded:

- *"To address cognitive load and support conceptual visualization, we employ animation and cartoons, which provide a dynamic representation of abstract quantum phenomena... which make abstract concepts easier to understand."[Instructor]*

Students echoed the instructor's sentiment, expressing appreciation for including these instructional resources.

- *"Maybe I was a little curious about some of the Nobel laureates and their work. I revisited the lectures multiple times to better grasp the concepts." [P2]*
- *"The lecture by Steven Garvin was there. Whatever I started understanding about superconducting qubits was from there." [P8]*

Similarly, when asked about the simulation and dynamic visualization slide content.

- *"The instructor put real effort into making the lecture slides. He incorporated animations to help us understand the concepts more clearly. For example, when explaining how circuits communicate, he used cartoons to visually demonstrate how communication happens within the chip, making it easier to grasp." [P2]*

- *"I personally prefer hands-on experiences, especially since the quantum nature is quite abstract. The instructor did an excellent job of designing the course material to make it more understandable. For instance, when explaining the Schrödinger equation for the hydrogen atom, the professor performed a detailed numerical derivation and used 2D and 3D animation to show each step. Later, we [students] have to perform similar steps with different n numbers. This helped me to understand how changing the quantum number* n *affects the outcome, making the concept much clearer." [P8]*

However, the inherent complexity of the quantum domain also posed a challenge when students lacked sufficient background knowledge.

- *"He shared research papers and links... I would usually take a quick look—just to see what it was. But I didn't go in-depth." [P2]*
- *"So I did mention that we had research papers to read and everything. In order to read a research paper, they mostly do not explain everything. I just have to keep looking up this term, that term. I did go through some of the papers. They were descriptive and good. The other ones—I was like, "This is written in Hebrew." I didn't understand anything." [P8]*
- *"So it would be much more efficient for me if I had done a course before. If I understood some of the basic concepts before coming to this course [Quantum Hardware course]."[P2]*

Theme 3: Learning Engagement
The instructor emphasized the role of assigned readings in fostering meaningful class discussions. He noted that students who engaged with the material beforehand contributed more effectively to discussions, leading to deeper analyses and critical thinking. He stated

- *"We carefully select research articles based on the topics we are going to study, ensuring that they align with the course content and provide students with relevant background knowledge." [Instructor]*
- *"The readings were assigned to ensure students come prepared with foundational knowledge allowing for deeper discussion rather than just surface-level explanation... it helps them [students] to ask better questions and critically analyze key concepts." [Instructor]*

Students recognized the value of these materials, noting that they enhanced their understanding and prepared them for class discussions. During the classroom observations, a high level of student engagement was observed. Even students who had not engaged deeply with the readings found the discussions valuable. By listening to summaries provided by their peers and engaging with critical questions raised, they were able to grasp key concepts and gain insights into the material. The indirect exposure enabled them to develop some understanding, even if they had not fully explored the articles independently. When prompted to discuss their experience with class discussion, both participants remarked that these sessions proved most advantageous for those who had thoroughly reviewed the assigned articles beforehand.

- *"The reading materials were valuable, but they required significant time to go through. Hardly anyone actually read the assigned readings. Sometimes, it would just be me and [class fellow] Jacob who made the effort to at least read through the paper or articles [Professor] provided. We were the ones who started the conversation [in the class]." [P8]*

Due to a lack of regular assessment, students admitted to attending class sporadically or focusing solely on presentation topics that would earn them a grade.

- *"I didn't really study any of the lectures. Sometimes, I didn't even care if I understood what was being taught." [P2]*

Theme 4: Assessments and Outcomes Presentations served as the primary mode of assessment, providing students with opportunities to delve into specific topics. However, this approach alone was insufficient to fully support a comprehensive understanding of the subject matter. A broader range of assessment methods might have enhanced the evaluation of learning outcomes and the practical application of concepts.

- *"The most I learned from this class was during our midterm and final presentations when we all delivered something on a topic." [P8]*
- *"The grade was based on the presentations and the final paper... There were just two presentations—one midterm and one final." [P2]*

Theme 5: Teaching Methodology
The teaching methodology prioritized independent learning, incorporating assigned readings and student-led discussions as central components. While some students commended this approach for promoting self-motivation and autonomy, others encountered difficulties due to insufficient background knowledge.

- *"What happened is that I don't understand most of the things he tells me to study, and it doesn't go much forward from there." [P8]*
- *"Sometimes, I only understand maybe 10 to 20 percent—at most—of what the professor is explaining." [P2]*
- *"He [the professor] was actually giving us technical inputs, right on the board, actually teaching. But most of the time, it was like he would assign some textbooks or papers and tell us to read." [P8]*

8 Results and Discussion

This section synthesizes the findings to address the following RQ's.

RQ-1 In what ways do dynamic visualization and simulation-based slides enhance students' understanding, applying, and retaining the nine key QIS concepts?
The quantitative and qualitative data demonstrate a notable improvement in students' comprehension of the nine key concepts of QIS. The exit survey indicates a significant improvement in all nine concepts. In particular, the quantum state and quantum measurement score was perfect (M = 4.00), while the quantum bit or qubit exhibited the highest overall improvement, with a mean score of 4.50. These results suggest that the use of dynamic visualizations effectively facilitated deeper understanding. The interview data further corroborate these quantitative findings, providing detailed evidence of how visual aids contributed to the learning process. For instance, both participants described how animation and simulation helped them visualize complex quantum concepts. These findings underscore the critical role of dynamic visualization and simulation-based content in bridging the gap between abstract quantum concepts and students' existing knowledge base.

RQ-2 How does integrating relevant quantum research articles into classroom instruction affect students' learning outcomes and engagement in class? is explored through classroom observations and students' reflections, which indicate that integrating quantum literature can deepen engagement and promote critical thinking. Classroom observation data reveal a high engagement level during sessions incorporating research articles.

Activities such as asking and answering questions related to these articles and whole-class discussions were prevalent. Student reflections on including research articles revealed both positive experiences and challenges. While some students appreciated the exposure to cutting-edge quantum research, others expressed difficulties understanding the content due to limited background knowledge (see Section 7.4 for details).

9 Discussion

The results of this study suggest success in improving the comprehension of quantum concepts, regardless of the initial familiarity levels of the participants. They also highlight critical insights into the challenges and opportunities in teaching quantum concepts. Three key themes emerged from the findings: the importance of scaffolding, the role of assessments in fostering engagement, and the need for institutional support for research-intensive instructors.

The reliance on advanced and complex materials without sufficient scaffolding posed significant barriers to student comprehension and engagement. Many students struggled to connect new and complex quantum concepts to their existing knowledge base, which hindered their ability to engage meaningfully with the material. Introducing concepts should be done progressively, tailoring instruction to students' current level of understanding.

The need for a broader range of assessment methods was voiced strongly. In previous iterations of the course, quizzes, homework, and other structured activities were offered. The Spring 2024 version of the course incorporated the previous assignments into in-class activities to reduce workload. In the next iteration, the instructor plans to bring back formative and summative assessments to reinforce learning and enhance engagement. The European Community Frameworks for Quantum Technologies (ECFQT) will still serve as a guide for designing the assignment [26].

The findings also emphasize the importance of institutional support for instructors teaching advanced research-intensive courses. Instructors often dedicate significant time and effort to researching and gathering up-to-date, relevant material for such courses. This dual responsibility of teaching and research can be overwhelming, particularly for instructors who must also manage additional institutional commitments. To address this challenge, institutions should consider revising TA and RA policies to reduce administrative burdens on research-heavy faculty members. Providing dedicated time and resources for instructors to focus on course preparation and delivery could lead to more effective teaching and a higher-quality learning experience for students.

10 Limitations

This study is limited in the following aspects: a small sample size that limits generalizability; a narrow focus on a specific QIS course, which restricts transferability; and reliance on self-reported data, which may introduce biases such as recall error and social desirability. However, it is important to note that graduate-level courses in this domain typically have low enrollment. In this study, there were 7 enrolled students and 3 auditors. The inherent complexity of quantum topics, coupled with the prerequisite knowledge of quantum mechanics and physics, often discourages students from enrolling, further contributing to the small sample size. These factors should be considered when interpreting the findings.

11 Conclusion and Future Work

This study underscores the significant potential of multimedia-based pedagogy and primary literature integration in enhancing student engagement and learning outcomes in quantum information science (QIS) education. The use of 2D and 3D visualizations and simulation-based slides effectively supported students in understanding complex quantum concepts, while the inclusion of research articles added contextual depth, connecting theoretical knowledge to real-world advancements. However, the effectiveness of these instructional strategies is often limited by students' insufficient background knowledge, which makes it difficult for them to understand complex primary research articles. This underscores the importance of prerequisite courses or preparatory modules to better support student learning. The findings strongly emphasize the need for a broader range of assessment methods to effectively support student learning and engagement. As it did for the activities in the lectures, the European Competency Framework for Quantum Technologies (ECFQT) will serve as a guide to ensure future assignments in the next iteration of the course align with key competencies and industry-relevant skills to foster critical thinking and active engagement. This study contributes to the growing body of knowledge on QIS instruction, offering insights for educators aiming to lower barriers of entry to the field, foster engagement in QIS courses, and better prepare students for the demands of the evolving quantum workforce.

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