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Board 432: Work in Progress: Immersive, Hands-On, and Interactive Quantum Information Science and Technology: Empowering Undergraduate Students in Quantum Computing

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WIP: Immersive, Hands-On, and Interactive Quantum Information Science and Technology: Empowering Undergraduate Students in Quantum Computing

Abstract

This work-in-progress (WIP) paper shares findings in Year 1 of "Collaborative Research: Innovating Quantum-Inspired Learning for Undergraduates in Research and Engineering (INQUIRE)," a 5-year Improving Undergraduate STEM Education project funded by the National Science Foundation. The project brings together quantum engineering and engineering education researchers at two public land-grant research universities, University of Florida, and University of Minnesota. The team aims to develop and establish a new paradigm for quantum-inspired learning for undergraduate students, which can then serve as a platform and may be adopted and customized across disciplines and institutions. The work detailed in this paper pertains to activities and developments at the University of Florida. We have developed new teaching modules for introductory Quantum Information Science and Technology (QIST) courses which encompass a range of instructional strategies, including multimedia-based learning (MBL), simulation-based learning (SBL), and hands-on programming for experiential learning. These tools enabled students to directly apply quantum concepts in their homework assignments, providing a more immersive experience with the course. This paper reports on the effectiveness of the newly designed teaching modules for the QIST software course "Introduction to Quantum Computing." A mixed-method approach was employed for the assessment. The immediate next steps for the course will be to address shortcomings in the next iteration of the course. Concurrently, we will apply a similar mixed-method approach to assess newly designed modules for the QIST hardware course offered in the Spring 2024 semester at the University of Florida.

Introduction & Background

Quantum computing is a field of computing that utilizes principles from quantum mechanics, a branch of physics that deals with the behavior of matter and energy at the atomic and sub-atomic scales. At the atomic and subatomic levels, electrons, photons, and ions act as qubits. In classical computers, bits are processed sequentially, performing tasks one after the other. However, in quantum computing, qubits can be entangled, a phenomenon where the state of two or more qubits becomes correlated. Unlike classical computers that use bits to represent information as 0's and 1's, quantum computers use qubits that can represent 0,1 or both simultaneously. Hence quantum computing allows for the development of novel algorithms capable of solving computational problems that are extremely challenging. Therefore, quantum computing is expected to lead to upcoming breakthroughs and holds the potential to revolutionize problemsolving in various areas such as machine learning optimization, AI, chemistry, cryptography, drug design, supply chain, and IoT security maintenance [1]–[4].

Technologically advanced nations have placed a distinct emphasis on advancing quantum technology through a comprehensive range of strategies as a means of fostering prosperity, progress, and overall well-being in the future [5]. Over the three decades, research in quantum technologies has transitioned from theoretical ingestion to experimental validation and development of prototype applications spanning diverse domains. As a result, numerous national and inter-governmental organizations in the USA, including the National Security Agency (NSA), Department of Energy (DOE), Department of Defense (DOD), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and National Aeronautics and Space Administration (NASA) have dedicated significant recourses toward the engineering of quantum technologies. Additionally, leading technology companies such as Microsoft, Google, Intel, IBM, Lockheed Martin, and several more research organizations around the world are seriously working on engineering quantum technologies [6].

To achieve this objective, efforts are being made to create a mutually beneficial connection between academia and the needs of industry by providing a sufficient and technically strong quantum workforce. Several tech corporations have released quantum development kits (QDKs) that enable experiential learning such as Google Criq, Rigetti Forest, IBM Qiskit, D-wave leap, strawberry fields, and Microsoft quantum development kits (QDK) [7]–[10]. As a result of the free availability of these QDKs, instructors can gain practical experience and demonstrate complex quantum concepts visually and practically, making quantum topics more engaging and comprehensible for students. These QDKs also make it possible for instructors to seamlessly integrate tangible applications of the quantum principles into their instructional approach. This fusion of practical resources elevates the overall efficacy of quantum education, equipping students with relevant skills and required knowledge to be part of a quantum-ready force. As quantum computers continue to gain computing power and the availability of quantum development kits increases, there is a growing demand for skilled workers in this field.

This work-in-progress (WIP) paper shares findings in Year 1 of "Collaborative Research: Innovating Quantum-Inspired Learning for Undergraduates in Research and Engineering (INQUIRE)," a 5-year Improving Undergraduate STEM Education project funded by NSF. The project represents a collaborative effort between quantum engineering and engineering education researchers from two public land-grant research universities, University of Florida, and University of Minnesota. The primary goal of the project is to enhance undergraduate engineering education in Quantum Information Science and Technology (QIST), specifically in response to pressing national challenges, such as the growing need for a QIST workforce.

The study aims to reduce the technical and cognitive barriers to enhance accessibility of QIST. It reports on "Introduction to Quantum Computing" (EEE 4423), which was initially offered in the year 2020 as a special topics course in the Department of Electrical and Computer Engineering (ECE) at University of Florida. The course, now offered every Fall semester, adopts a comprehensive approach to learning about quantum technology, covering both software and hardware aspects of the field. In Fall 2023, the research team undertook a significant redesign of the course of the course, implementing new instructional strategies to enhance the learning outcomes. This study aimed to systematically identify the barriers students might encounter while learning the EEE 4423 course. Drawing on insights from the course's previous semesters, the instructor introduced simulation-based homework assignments. These SBL assignments are strategically designed to align with the 9 key concepts of Quantum Information Science (QIS), reduce the cognitive load experienced by students, and facilitate deeper understanding of the material.

Motivation

The team aims to develop and establish a new paradigm for quantum-inspired learning for undergraduate students, which can then serve as a platform and may be adopted and customized across disciplines and institutions. The work detailed in this paper pertains to activities and developments at the University of Florida. Specifically, this WIP addresses two research questions in the context of the Quantum Information Science and Technology (QIST) software course, Introduction to Quantum Computing:

(1) What are the barriers undergraduate students face on their pathways to building a knowledge base in QIST?
(2) How does the Innovating Quantum-Inspired Learning for Undergraduates in Research and

Engineering (INQUIRE) project address the knowledge base need and lower the barriers to QIST entry?

As outlined in the literature [11]–[16], various factors, such as learning environment, design and organization of the curriculum, assessment, feedback, and learning new tools outside the student's comfort zone can impede learning. This research focused explicitly on identifying factors that could serve as barriers within the newly designed modules for the Introduction to Quantum Computing course (EEE 4423).

Course Structure of Introduction to Quantum Computing (EEE 4423)

The course syllabus was designed to cover the 9 key concepts for Quantum Information Science (QIS) learners [17]. This course aims to provide engineering students with an in-depth understanding of quantum computing software as well as some hardware aspects. The curriculum covered the fundamental concepts of quantum computing and the intricate process of constructing its hardware in a self-contained manner. The course was divided into two parts. The first part of the course covered the fundamental concepts of quantum mechanics, such as superposition and entanglement. The second part of the course focused on the hardware realization of quantum computing technology. The third and final part of the course covered numerous examples of quantum computing algorithms that apply the concepts. The 3-credit course had one pre-requisite course, i.e., Linear Algebra. The course draws from select textbooks and reference material [18], [19] underpinning its comprehensive nature and providing a structured framework for learning. The weekly list of topics of EEE 4423 is shown in Table 1.

The course spanned one semester, during which students attended three 50-minute lectures per week. In addition to the lectures, weekly Zoom office hours were held to facilitate direct engagement with the instructor and provide personalized support to the students.

Table 1: EEE 4423 Timeline

Weeks #	**Topics**
Week 1	Linear Algebra
Week 2	Intro to quantum mechanics in matrix form
Week 3	Intro to quantum mechanics in matrix form
Week 4	Superposition and entanglement
Week 5	Quantum gates and quantum circuits
Week 6	Superconducting technology for quantum computing
Week 7	Semiconductor technology for quantum computing
Week 8	Semiconductor technology for quantum computing
Week 9	Mid-Project
Week 10	Optical technology for quantum computing
Week 11	Introduction to Deutsch-Jozsa algorithm and Grover's algorithm
Week 12	Quantum Fourier transform and Shor's algorithm
Week 13	Quantum variational algorithm and its application
Week 14	Final Project and Presentation
Week 15	Final Project and Presentation

The assessment included a mid-term project that accounted for 15 percent of the overall grade. Within the framework, each student must choose a research paper, preferably aligned with their term project, within the quantum computing domain. The grading rubric for the presentation was threefold. Firstly, the presenter's ability to explain the problem, and solution, and evaluate the outcomes was evaluated. Secondly, the quality of responses to audience questions was assessed. Finally, the content and coherence of the presentation slides were scrutinized. Homework assignments held a weightage of 10 percent, serving as an ongoing evaluation of student's comprehension and engagement. The culminating exam, which encompassed a comprehensive evaluation of the course content, held the highest weightage at 35 percent. The final project at the end of the semester constituted 40 percent of the grade.

Multimedia-based Learning Materials

The project team adopted the multimedia-based learning (MBL) technique to design the lectures for this course. The topics covered in quantum-related subjects involve extensive mathematical calculations without visual representation. This posed difficulties for students in understanding the concept. To tackle this challenge, the project team developed new lectures based on Mayer's multimedia principles [20], and cognitive load theory [21]. Topics were explained with the support of static and dynamic images in the form of visualization for better expression and comprehension of the concepts. One such example is shown in Figure 1.

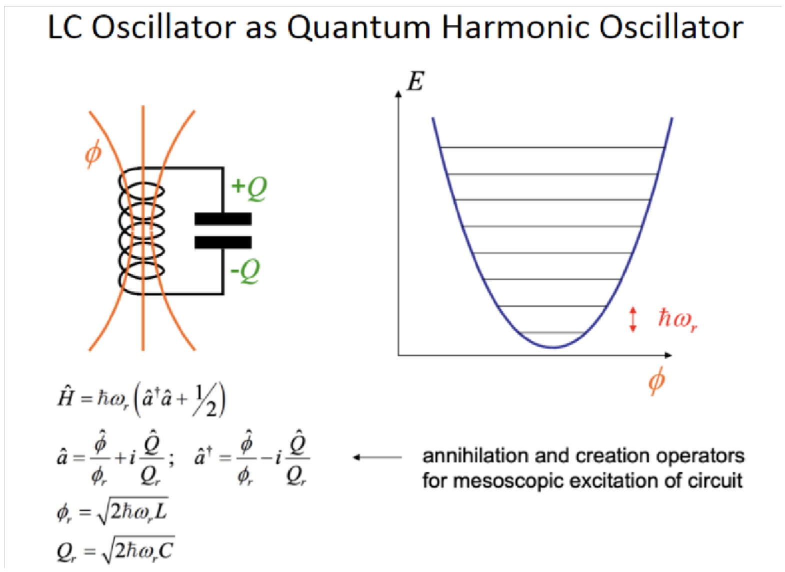

Figure 1: LC oscillator as a Quantum Harmonic Oscillator

Learning Objectives of the Assignments

The homework assignments in the EEE 4423 course were designed to provide students with a hands-on learning experience. There were 5 assignments, posted bi-weekly. Each homework assignment was designed to touch on 9 key concepts for Quantum Information Science (QIS) learners [17].

Homework 1 aimed to equip students with a solid foundation in linear algebra and quantum computing. Upon completing this homework, students should be able to grasp the intricacies of QIS and demonstrate proficiency in applying mathematical principles to quantum gates, matrices, computer eigenvectors, and eigenvalues through linear algebra.

Upon completing Homework 2, students should attain a comprehensive understanding of computing rotation matrices and their significance in manipulating quantum states. This learning objective was aligned with quantum states, entanglement, and quantum computer concepts of QIS. Homework 1 and 2 consisted of several problem questions that required mathematical calculation to demonstrate a solid understanding of the Linear Algebra and Quantum Mechanics concepts.

The objective of homework assignments 3, 4, and 5 is to integrate theoretical concepts with hands-on applications, facilitating a better understanding of quantum computer concepts and challenges.

In Homework 3, the question emphasized the exploration of quantum principles, analysis of quantum states, understanding the impact of parameter change engaging in simulation on the Quantum Spice tool developed by IBM. The objective of this homework was to provide students with practical insights into the behavior of superconducting qubits and their interactions with microwave resonators. To assist the students in navigating through this simulation tool, a step by-step guide was provided by the instructor.

Homework 4 provided a comprehensive understanding of spin quantum gates based on semiconductor quantum dots. The objective of this homework is to equip students with practical abilities in simulating quantum gates, interpreting simulation results, and comprehending how various factors might influence the effectiveness of quantum systems.

In Homework 5, students were expected to set up the Qiskit quantum computing framework on their computers. After that, they created and analyzed a specific quantum circuit to understand the effect of noise on quantum devices by simulating noise in different quantum states. The instructor provided a step-by-step guide to set up Qiskit along with a YouTube tutorial.

The final project focused on the themes of quantum computing covered in the class and included sections such as motivation, background, technical approach results, discussion, and conclusions. Supported by the execution of calculations, modeling, or simulations.

Table 2 offers a summary of how each question in these homework assignments mapped to 9 key concepts of QIS.

Table 2: 9 Key QIS Concepts Mapping on Homework Assignments

9 Key Concepts/ Homework	**HW 1**	**HW 2**	**HW 3**	**HW 4**	**HW 5**
Quantum Information Science (QIS)	✓	✓	✓		✓
Quantum State	✓	✓	✓		✓
Measurement				✓	
Quantum Bit, Or Qubit		✓		✓	
Entanglement				✓	✓
Coherent			✓	✓	✓
Quantum Computers	✓	✓	✓		✓
Quantum Communication				✓	✓
Quantum Sensing	✓			✓	

Research Method

In our study, we adopted an interpretive paradigm, a framework in research that places importance on understanding and interpreting the subjective experience [22] to identify potential barriers undergraduate students face on their pathway to building a knowledge base in the EEE 4423 course.

We used a mixed-method approach to answer two research questions: (1) What are the barriers students face on their pathways to building a knowledge base in QIST? (2) How does the Innovating Quantum-Inspired Learning for Undergraduates in Research and Engineering (INQUIRE) project address the knowledge base need and lower the barriers to QIST entry?

Methodology

Our methodology is divided into two phases, In the first phase, at the start of the Fall 2023 semester, we interviewed EEE 4423 course instructor. In that same week, we administered a baseline survey (Appendix A) to the students enrolled in the course (n=18). A two-week window was given to students to respond to the baseline survey. Additionally, to gather more information, a team of two researchers conducted several classroom observations throughout the semester. The primary objective of these classroom observations was to scrutinize the instructional environment and teaching methodologies employed throughout the semester.

In the second phase, after the completion of the semester, we interviewed the instructor again. We sent several requests to 18 students to participate in an exit survey. Only four participants responded and agreed to participate in the exit survey and exit interview. Participants were modestly compensated for their time. Both surveys utilized a combination of open-ended and Likert scale format questions (Appendix B). Both surveys underwent a face and content validation process. During the face validation base, we conducted three rounds of assessments to ensure that the survey questions were clear and understandable to participants. Simultaneously, we carried out three rounds of content validation, which involved consulting subject matter and engineering education experts to assess the relevance and comprehensiveness of the survey content.

Data Collection

Phase 1: Interview with the Instructor & Student Baseline Survey

Interview with the Instructor: A 45-minute Zoom interview was scheduled with the course instructor, The semi-structured interview's purpose was to gain insights from the instructor's perspective regarding the course content, learning objective of homework assessments, and student learning behavior.

Student Baseline Survey: The primary objective of the baseline survey was to seek information about various aspects of academic background, motivation, programming, and mathematical abilities before exposure to quantum concepts and activities. For those who encountered quantum concepts, the survey measured their familiarity with 9 key concepts of QIS. Participants were asked about their likelihood of pursuing a quantum-related career. The baseline survey also explored, research interest, a listing of three topics that they were most interested in learning in the EEE 4423 course, inquiring about any specific areas of quantum computing applications that might interest them, and what are their expectations from this course. The survey's main aim was to enable the instructor to better understand the students as learners and use this information to enhance the course learning experience.

Classroom Observations: Over the semester, two individuals undertook a comprehensive observation of the introduction to quantum computing class using the Classroom Observation Protocol for Undergraduate STEM (COPUS) [23]. The classification code included a range of student actions, including listening, answering, and posing questions, engaging in discussion, presenting, participating in group activities, individual thinking, and waiting. Instructor actions were categorized, covering aspects such as lecturing, real-time writing, demonstrating, providing feedback, posing questions, administering clicker questions, and engaging in one-on-one discussions. This detailed observation facilitated a team of researchers to investigate the classroom dynamics, encompassing student and instructor engagement, teaching strategies, and alignment with the learning objectives of the EEE 4423 course.

Phase 2: Instructor Exit Interview, Student Exit Survey, Student Exit Interview

Instructor Exit Interview: A 45-minute Zoom interview was scheduled with the professor. The conversation revolved around the instructor's observation of student difficulties with lectures, homework assignments, and projects throughout the course. Additionally, insights were sought regarding the instructor's reflection on the overall EEE 4423 course experience.

Student Exit Survey: The fundamental purpose of the exit survey was to record students' perspectives on lecture content, homework assignments, overall course experience, and the challenges they encountered during the EEE 4423 course. The survey also aimed to assess the perceived difficulty of the workload and homework assignments. In the end, students self-assessed their current level of understanding of the 9 key concepts introduced in the course. Additionally, the survey aimed to identify any barriers that might have posed challenges to understanding these 9 key concepts of QIS.

Student Exit Interview: Following this student exit survey, a 45-minute semi-structured interview was conducted with the participants to validate and substantiate the findings derived from the exit survey.

Results and Data Analysis

Interview with the Instructor

During the initial interview, the professor highlighted the diverse academic backgrounds of students taking the quantum course. In response to the question of whether academic background influences the understanding of quantum computing concepts. He stated:

> *"Yes, it depends on the students' backgrounds. Some students may be strong in computer science and coding but struggle with quantum physics concepts. Others, solid in quantum mechanics, may find it challenging to connect the two. The spectrum of students is wide, and their strengths and weaknesses vary. The introduction to quantum physics can be troublesome, especially for those with no background in it."*

When asked if he had noticed any topics with which students struggled in his previous quantum computing course. The professor responded:

> *"Topics related to quantum physics can be challenging, especially when delving into the core concepts. For example, weeks 6, 7, and 8, which cover superconducting technology for quantum computing, involve abstract concepts from physics and semiconductor behavior. Students tend to struggle the most during these weeks, requiring a solid foundation before and after."*

When inquired how he addressed this challenge, he incorporated a couple of lectures and additional reading materials that covered these concepts.

> *"We included introducing the fundamentals of quantum mechanics, explaining the physical implementation of quantum computers, and discussing examples of quantum computing algorithms."*

Baseline Survey

The survey includes insight from a diverse group of eighteen participants, comprising 4 undergraduate students from the junior level, 6 undergraduates from the senior level, and 8 graduate students, representing various departments such as Electrical, Computer and Civil Engineering, Math and Physics, and Computer Science.

In response to the question "Have you participated in any of the quantum-related activities before taking this course. Activities such as seminars, reading relevant literature, or covered in previous courses," 77.78 % (14 out of 18) students mentioned that they had never engaged in any quantum-related activities. In contrast, 16.67% (3 out of 18) students reported having read a quantum-related book, and only 5.56% (1 out of 18) mentioned attending a seminar. When inquired asked how familiar they are with the basic principles of quantum computing. 55.56% (10 out of 18) respondents expressed a lack of familiarity with 9 key concepts of QIS before taking this course. Conversely, 27.78 % (5 out of 18) indicated a slight level of familiarity with these concepts. While only 16.67 % (3 out of 18) participants reported a moderate familiarity with the principles.

Responses to two open-ended items from the baseline survey (Appendix A) were analyzed. First, each student was asked to outline three key aspects they were eager to learn from the course. The responses from Students 1,2,3,4, and 5 showcased a shared interest in grasping the logic behind quantum computing. Students seemed particularly enthusiastic about understanding the fundamental reasoning that underlines the quantum computational process, for example.

Student 1: *How does quantum mechanics work, can quantum computing be a new technological race and discovery that benefits society, and how can I be involved in quantum computing in the tech industry?*

Student 2: *I want to learn Quantum Algorithms, Quantum Physics, and the necessary hardware topics. I also want to know how quantum computers process so fast computation. What is the mathematical logic behind that?*

Student 3: *how quantum computing works, learning about the mathematical foundation of solving quantum computing course, expanding my knowledge of quantum mechanics in general.*

Student 4: *I am interested in how Quantum technology for semiconductors works. How do quantum cryptography and physics behind quantum computers work?*

Student 5: *How does quantum entanglement work?*

Secondly, each student was asked to pose three questions related to the quantum computing course syllabus or general questions about the quantum computing field. Responses from the students are below:

Student 1: *Are we going to build a functional quantum circuit in this course?*

Student 2: *I want to understand the connection between quantum computation (or quantum Logic gate) to quantum hardware. Are we going to do any lab work?*

Student 3: *How to maintain qubits in a stable state with minimum error and redundancy while performing computation? Can we simulate dynamic processes with a quantum computer?*

Why do larger objects show relative behavior when those objects are made of particles that show quantum behavior (Why does the superposition collapse on a larger scale? Do all the particles require special conditions to show quantum behavior?

Based on the baseline survey responses, students were curious to gain knowledge about quantum computing. The findings from this baseline survey provided valuable insights to instructors to enhance the course content as per learner needs.

Classroom Observation

The COPUS protocol systematically recorded all the activities occurring during a 50-minute class period, detailing the occurrence within each 2-minute time interval. The utilization of the COPUS protocol facilitated a team of researchers to evaluate various aspects of the course, including student-professor engagement, teaching methodologies, and student engagement, during class time.

Predominantly, students were listening, constituting 88 % of the class activity, followed by answering questions at 23% and asking questions at 12 % (Figure 2). Notably, no responses were recorded for activities such as whole-class discussions and group discussions during the observed class period.

In the context of course instructor activities during the observed class sessions. The predominant actions were lecturing (Lec) and real-time writing (RtW), constituting 88% and 65 % of total instructor responses, respectively. Other notable engagements included posing questions (PQ), answering questions (AnQ), and moving through the class to guide ongoing work (MG), representing 35 %, 27 %, and 58% of total responses. Intriguingly, there were no recorded responses for activities involving demonstration-on-one interaction with students. The graphical representation of the class observation is shown in Figure 2.

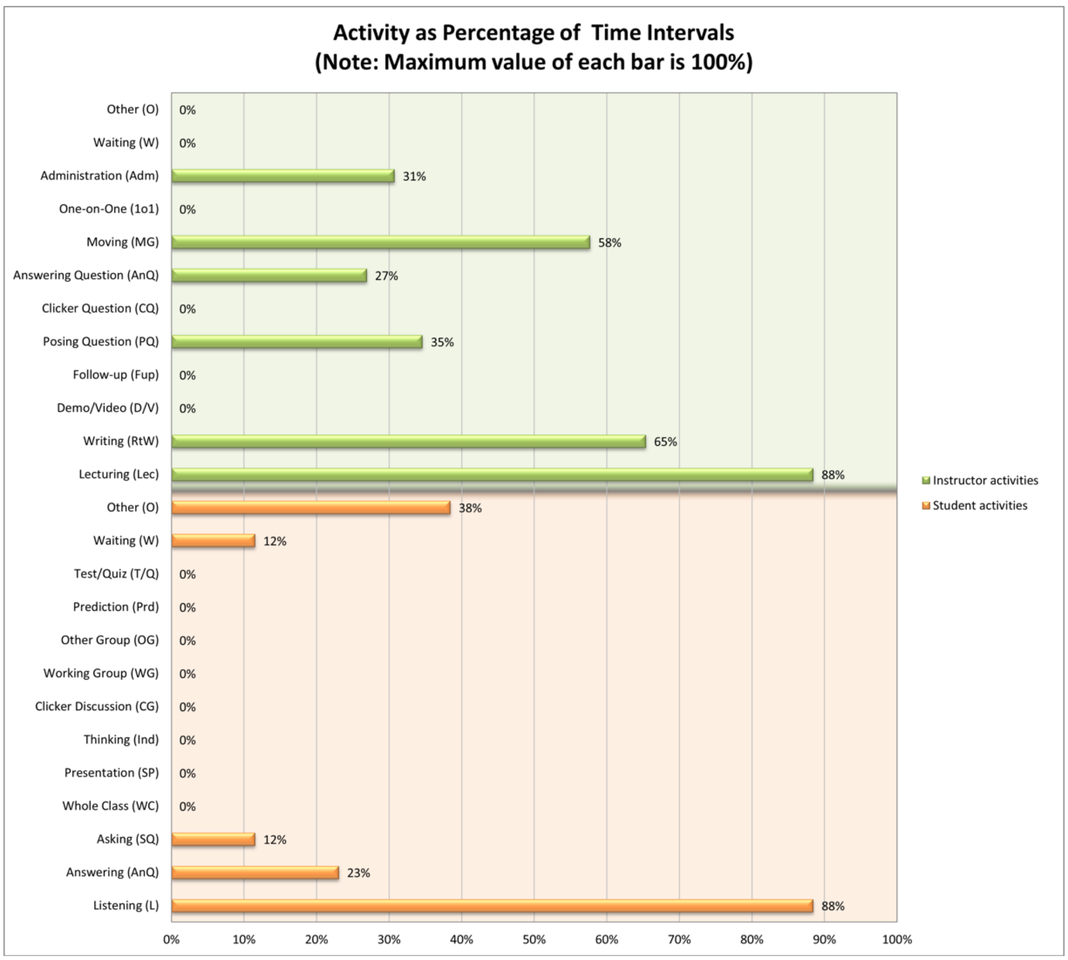

Figure 2: Classroom Observation Data

During the class observation, both observers discerned a similar trend, noting an atmosphere that was somewhat subdued. Students seemed content with the passive consumption of information, focusing on the lectures rather than actively contributing to discussions or seeking to deepen their understanding of the topic. This observation highlights a notable lack of overall engagement during the class time,

Quantitative Analysis of the Student Exit Survey

The purpose of the exit survey (Appendix B) was to draw comprehensive insights related to the course alignment with students' expectations. The exit survey consisted of 30 open and closed ended questions to capture students' perspectives on lecture and class experience and the challenges encountered during the course. Additionally, the survey aimed to identify any barriers that might have posed challenges to understanding these 9 key concepts of QIS. Moreover, towards the end of the exit survey, students were asked to report on their current level of understanding of the 9 key concepts of QIS that were introduced in the course. The key findings of the exit survey are explained below.

The exit survey, distributed to 18 students enrolled in the Fall 2023 course, elicited responses from 4 participants, resulting in a participation rate of 22.22 %. Of these, only three agreed to participate in the follow-up interview. Given the relatively low participation rate, a comparative analysis was undertaken. This analysis aligned the individual participants' responses with their baseline survey submissions, aiming to extract deeper insights despite the limited engagement.

Participants 1, 2, 3, and 4 reported a lack of familiarity with the 9 key quantum concepts before taking the EEE 4423 course. Post-course engagement, 3 participants conveyed the acquisition of substantial knowledge, while 1 participant reported a moderate increase in their understanding.

In response to items 3-6 of the exit survey (Appendix B), all four participants indicated a moderate level of challenges in comprehending content but found the workload reasonable. This sentiment was attributed to the clarity and adequacy of the lecture content. When asked to identify the most engaging and effective aspect of the course contributing to their learning, all four participants unanimously selected lecture content, simulation-based homework exercises, and class projects. However, a consensus emerged on the absence of student-to-student and student-to-professor engagement.

In response to the question, "Did the quantum computing course provide sufficient hands-on experience with quantum computing tools and simulations," a range of perceptions emerged among the four participants. Two participants reported a high level of satisfaction, while another participant expressed a favorable view and reported it as very useful. However, one participant conveyed that the hands-on experience was less useful, as it included examples that were overly simplistic, provided too much guidance and did not trigger critical thinking.

In the exit survey, participants employed a self-assessment tool comprising five levels, ranging from challenges in recalling information to a thorough understanding of the 9 key concepts of QIS. Table 3 presents an analysis of participants' self-assessment responses, providing insight into their perceived comprehension across the specified key quantum concepts.

Table 3: Descriptive Statistics of Participants Self-assessment of 9 key concepts of QIS

Field	Min	Max	Mean	Median	SD	Variance	Responses
Quantum Information Science	2.00	4.00	3.25	3.50	0.83	0.69	4
Quantum State	4.00	5.00	4.75	5.00	0.43	0.19	4
Quantum Measurement	4.00	5.00	4.25	4.00	0.43	0.19	4
Quantum bit or Qubit	4.00	5.00	4.75	5.00	0.43	0.19	4
Entanglement	4.00	5.00	4.75	5.00	0.43	0.19	4
Quantum Information Application	2.00	4.00	3.00	3.00	0.71	0.50	4
Quantum Computers	4.00	5.00	4.25	4.00	0.43	0.19	4
Quantum Communication	2.00	4.00	3.25	3.50	0.83	0.69	4
Quantum Sensing	2.00	3.00	2.25	2.00	0.43	0.19	4

Qualitative Analysis of the Student Exit Survey

Following the exit survey's administration, an invitation for a Zoom interview was extended to all participants to share more insights into their course experiences. Subsequently, individual 45-minute Zoom interviews were conducted individually with three participants. The data from these interviews was then analyzed using NVivo software. Through this analysis, three overarching themes emerged, namely 1) Background Knowledge, 2) Learning content, and 3) Class engagement. Each of these themes directly ties back to the research questions as shown in Table 4.

To ensure a comprehensive qualitative analysis of the study, interviews were transcribed to capture all the details of the participants' responses. Two coders then independently undertook the initial coding cycle, to identify patterns and themes within the data. Both coders also engaged in the reflective process to record their first impressions, questions that arose, and patterns they observed in the data. Based on the first cycle of coding a codebook was generated. In the second cycle of the coding, both coders compared the coded segment as per the codebook to assess the consistency of their analysis using Cohen's Kappa which resulted in a score of 0.80.

Table 4: Research Question Mapping with Themes

Research Questions	Themes
RQ 1: What are the barriers undergraduate students face on their pathways to building a knowledge base in QIST?	<u>*Background Knowledge:*</u> Students may face barriers due to insufficient prior knowledge in quantum physics and quantum mechanics fields.
	<u>*Learning resources:*</u> The rapid pace of lectures can exacerbate issues, as students may struggle to keep up with complex topics, impacting comprehension and retention. Challenges in completing assignments and projects without a strong foundation in quantum computing courses.
	<u>*Class engagement:*</u> Lack of background knowledge and difficulties with pace can affect active participation. Students may feel less confident in discussions, hindering their overall engagement in the course
RQ 2: How does INQUIRE address the knowledge base need and lower the barriers to QIST entry?	How effective was the use of simulation-based *homework assignments*

Three themes were identified that addressed the RQ 1" What are the barriers undergraduate students face on their pathways to building a knowledge base in QIST". A detailed analysis of each theme is presented below.

Background Knowledge

As the course instructor mentioned in his initial interview, most of the students in the quantum computing course struggled because they did not have sufficient knowledge about quantum physics and quantum mechanics. We have also observed a similar trend in the course as the students who had no background knowledge faced difficulty with understanding basic concepts of quantum computing.

> ***Participant 1:*** *I felt like I didn't have background knowledge of quantum physics and quantum mechanics. There was a lot of background information required beyond just linear algebra and basic mathematics in this course.*

> ***Participant 2:*** *I was confused about how quantum physics and quantum mechanics work. But I think if the instructor had provided more information about these topics, it would have been nice.*

Learning Resources

The main sources of learning materials used in the Introduction to Quantum Computing course were lectures, course books, and the latest research articles. However, there were some concerns which were reported by the participants that the course needs more additional resources.

> ***Participant 1:*** *I found the hardware lectures challenging to engage in. The professor seemed to ramble a lot. lectures provided a good introduction, but there were areas where it fell short.*

> ***Participant 2:*** *I find the way hardware concepts were presented a bit confusing and at a fast pace. Now, I understand there are different methods for implementing a qubit, but during the lectures, it would have been clearer if the professor had taught them in a specific order. The way it was presented made all types of qubits seem the same.*

When asked about which topic or concepts difficulty were difficult to understand, all three participants highlighted a couple of concepts that would benefit from more attention in terms of designing and presenting the content:

> ***Participant 1:*** *The topic related to Oracle was challenging as it was not presented well. I don't mean to say negatively, maybe the way lecture slides were made was not helping me to understand the topic. Moreover, quantum communication and quantum sensing were particularly challenging. The physical aspects, like qubit-to-qubit communication and reading data from the qubit, were complex, and I still have many questions about those...*

> ***Participant 3:*** *I think Oracle. I remember we talked a lot about an oracle that was strange to me. I hadn't known, a little to no idea what that was. I understood the functionality, but I did not understand the concept. You know what, that was difficult.*

When we asked participants to identify the least understood principles from the 9 key concepts of QIS. They responded:

> ***Participant 2:*** *Quantum communication, quantum sensing, and quantum information. I'm not sure we got into that much.*

> ***Participant 3:*** *The math that's presented in the algorithm is a big jump compared to the other concepts because, like I remember when he introduced us to qubit states or how they change, the lecture slide shows the example. But I remember him writing on the board that you could do it like… visualizing that one qubit … I feel like, maybe he had one qubit example in simulation while teaching the topic. It would make more sense and help us understand better.*

Homework Assignments

When inquired about did the simulation-based homework assignments helped them understand the 9 key concepts better. The participants responded:

> ***Participant 1:*** *The homework assignments seemed to be less difficult than the content being taught. The assignments 3-5 in the course lacked critical thinking and were too tutorial based. But yes, it helped me understand the concepts.*

> ***Participant 3:*** *Simulation-based homework exercises helped me a lot to understand those concepts. I still have some questions about those 9 key concepts, but I think that for an introductory course, the instructor did a good job. Homework 3 helped me to understand how microwave resonators will respond if we change the capacitance and I think the inductance value does too...*

Lack of Engagement

The third theme that emerged from the study was the lack of engagement between one-to-one professor-student engagement and student-to-student engagement during class. The lack of engagement is crucial to address, as it significantly impedes the learning process. Both participants mentioned that:

> ***Participant 1:*** *There wasn't enough student engagement such as student question answers etc. during the class lectures. I think this also hindered my ability to grasp the topics effectively. Since no one was asking the questions in the class… it seems the class environment was tense.*

> ***Participant 3:*** *I believe the professor was quite open to questions during class. However, I hesitated to ask the question in class time because I was concerned it might waste other students' time. It seems the classroom environment, which the professor establishes, plays a major role in encouraging students to ask questions. Sometimes, students need encouragement from professors to ask what might be seen as silly questions. Yet, those questions can help clarify any doubts about the concepts.*

At the end of the exit survey and interview participants were asked what improvements could be made in the future course the responses are stated below:

> ***Student 1:*** *The hardware aspect of quantum computing could be more developed. The homework assignments should have questions that can engage critical thinking.*

Student 2: *Focus more on real-world applications and real-time coding can further improve the hands-on experience. The homework assignments were too easy.*

Student 3: *More involved lab-based assignments that highlight a key concept of 9 key concepts of QIS.*

Discussion

This study used a mixed-method approach to explore potential barriers faced by undergraduate students during the Fall 2023 Introduction to Quantum Computing course. The significance of multimedia-based learning cannot be overstated [24]. Numerous studies have substantiated the impact of multimedia-based learning on the education system [25], [26]. In newly designed lectures all three participants of the study reported that lecture content, simulation-based activities, and homework assignments were engaging and helped them understand the concepts better.

In the interview, students expressed concerns related to the hardware component of the course. Student feedback revealed concerns about certain topics being challenging to comprehend due to several factors such as too many complex mathematical calculations. Students also highlighted the importance of including homework questions that prompt critical thinking skill development. These concerns have been noted and will be taken into consideration for improving future iterations of the course. Concurrently, based on these findings, the project team will make appropriate changes in the newly developed modules for the QIST hardware course at University of Florida during the Spring 2024 Semester.

Limitation

The study is subject to limitations that should be considered. Initially, the participants' group comprised 18 individuals, but only three participants responded to both the exit survey and exit interview. This reduced participation places constraints on the generalizability of the findings.

Secondly, the researcher investigated only academic factors. We did not consider other potential barriers like economic and social factors in this research. This means that our findings might not cover all the difficulties students face in QIST learning. So, when interpreting our results, it is important to keep in mind that we specifically focused on the identification of potential barriers and how these barriers can be lowered to reduce the technical and cognitive load on students. More detailed studies might be needed to understand the broader challenges students encounter in this field.

Conclusion and Future Directions

The findings of this study underscored the significant impact of multimedia-based learning (MBL) and simulation-based learning (SBL) as effective teaching methodologies for introducing quantum computing concepts. The inclusion of SBL homework, designed around the 9 key concepts of QIS, has improved the course applicability, ensuring it meets the practical demands of the quantum field. Insights from classroom observations were shared with the professor to foster a more interactive and engaging learning environment for future iteration of this course. Reflecting on these insights, we are committed to implementing targeted modification to the hardware segment of the quantum course in the ongoing Spring 2024 semester.

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Appendix A

S. No	Student Baseline Survey Items
General Questions	
1.	Your Full Name
2.	What department are you in?
3.	State your major. Field of study
4.	Where are you in your academic studies?
Likert Scale Items Scale ranging from 1 (indicating the lowest) to 5 (representing the maximum)	
5.	Have you encountered quantum concepts or topics in any other academic course or subject, including online courses?
6.	Have you participated in any of the following quantum-related activities before starting this course? (Check all that apply)
7.	How familiar are you with the basic principles of quantum computing? Please refer to 9 key concepts of quantum before providing your answer.
8.	To what extent do you feel confident in your ability to programming languages?
9.	To what extent are you familiar with the practical applications of quantum computing in various industries?
10.	How confident are you in your ability to apply mathematical concepts to solve complex problems?
11.	How important do you think quantum computing will be in the future of technology?
12.	How likely are you going to pursue a career in a field related to quantum computing or quantum information science?
Open Ended Questions	
13.	What are your main objectives for taking this quantum course?
14.	What is your preferred learning style or method? How do you feel you learn best?
15.	Please describe your research interests or latest research experience in two or three sentences. If you do not have experience in research, simply put N/A

Appendix B

S. No	Student Exit Survey Items
General Questions	
1.	Your Full Name
Likert Scale Items Scale ranging from 1 (indicating the lowest) to 5 (representing the maximum)	
2.	Prior to this course, how familiar were you with quantum computing?
3.	How much knowledge have you gained about [a link to "9 Key concepts of Quantum" through Google Drive is mentioned here] through this course?
4.	How challenging was the Quantum Computing course?
5.	How reasonable was the workload for the quantum computing course?
6.	Which aspects of the course did you find most engaging and effective for your learning? (Check all that apply)
7.	How effective was the use of visual aids in lectures (e.g., diagrams, simulations) and the additional resources in explaining quantum concepts?
8.	Did you utilize external resources such as (websites, blogs, and online tutorials) to help your learning in the quantum computing course? If yes, please share the URL, etc. otherwise please put N/A
9.	How effective were the assessments (Quizzes, Homework assignments, Projects, and Presentations) that helped you apply the concepts and techniques learned in this course?
10.	Did the course provide useful hands-on Homework exercises that helped build your understanding of 9 key concepts of quantum?
11.	Which homework assignments helped build your understanding of the 9 key concepts of quantum? (Check all that apply)
12.	What did you like the most about the quantum computing course? (Lectures, Homework exercises, Project, and Presentation, Simulations on online tools)
13.	What is your preferred online simulation tool for completing homework assignments?
14.	Did the course adequately cover the Quantum Information Science Technology topic?
15.	Did the course adequately cover topics related to the Quantum State?
16.	Did the course adequately cover the Quantum Measurement topic?
17.	Did the course adequately explain Quantum bit or qubit topics?
18.	Did the course adequately explain Entanglement?
19.	Did the course adequately address Quantum Information Application?
20.	Did the course adequately address your understanding of Quantum Computing
21.	Did the course adequately address topics related to Quantum Communication?
22.	Did the course adequately cover the Quantum Sensing topic?

23.	How confident do you feel in applying quantum computing principles to real-world problems?
24.	Please rate your understanding of the following 9 key quantum Concepts after taking this course.
Open Ended Questions	
25.	Have you encountered any challenges in understanding the 9 Key Concepts of Quantum Computing course? If yes, please specify. Otherwise please write No
26.	Are there any difficult topics in the Quantum Computing syllabus that you find particularly challenging?
27.	Please mention any other challenges you faced that acted as a barrier in learning 9 key concepts of Quantum throughout the semester. (If you do not face any challenges, please add N/A)
28.	In your opinion, what initiatives or changes could be implemented in the next semester to address the barriers faced by you in this course?
Likert Scale Items Scale ranging from 1 (indicating the lowest) to 5 (representing the maximum)	
29.	Overall, how satisfied were you with the quantum computing course?
30.	How likely are you going to recommend this course to others?

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