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Leveraging Open Source Tools to Teach Quantum Computing Foundations: Bridging the Future Workforce Gap in the Quantum Era

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Abstract

The advent of the post-quantum era introduces significant challenges and opportunities, particularly a pressing workforce gap in quantum computing education and skills. In response, public and private stakeholders are actively enhancing their efforts to advance quantum education. For instance, IBM's recent pledge to upskill 30 million individuals by 2030 specifically emphasizes quantum computing and cryptography. Similarly, the White House Office of Science and Technology Policy, and the U.S. National Science Foundation, have engaged in quantum education discussions at a summit that brought together leading educators and professionals in Quantum Information Science and Technology (QIST) to strategize on future workforce development. Additionally, NIST is gearing up to unveil its post-quantum cryptography standard in the near future.

Despite these efforts, collaboration across sectors in aligning quantum education approaches needs more focus. As experienced educators and researchers, our observation is that while cybersecurity education has witnessed extensive collaboration across government, industry, and academia, quantum education in some sectors is not receiving the attention as highlighted by government initiatives. We propose a systematic approach, leveraging established frameworks like NICE, to integrate quantum computing education into mainstream curricula to ensure that industry will not have the large gap of filling jobs as the cybersecurity sector is currently experiencing.

We present an analysis of two courses introduced in our CS department: "Introduction to Quantum Computing," and "Quantum Computing II." We outline the course modules specifically crafted to heighten students' quantum awareness and curiosity as they will be confronted with opportunities and issues related to quantum computing in their software engineering careers. Our student survey results, utilizing a Likert scale ranking, indicate a significant increase in students' interest and curiosity in quantum concepts, as well as their eagerness to further explore quantum computing. These results that we are meeting our educational objectives.

Introduction

Quantum computing represents a paradigm shift in the field of computational science, leveraging the principles of quantum mechanics. Unlike classical computing, which uses bits to process information in a binary format, quantum computing uses quantum bits, or qubits, that can exist in multiple states simultaneously [1]. This unique feature enables quantum computers to process vast amounts of data at unprecedented speeds, making them incredibly powerful tools for specific types of computations predicted to provide us with new technological innovations and also needs to safeguard our current infrastructures [2]. It holds the potential to revolutionize various fields, including cryptography, drug discovery, financial modeling, artificial intelligence, and more. Quantum computers can solve complex problems that are currently beyond the capabilities of classical computers, such as simulating large molecular structures or optimizing large-scale systems in logistics and manufacturing [3].

However, as this technology rapidly advance the challenges of the quantum workforce gap has emerged. There is a growing demand for professionals skilled in quantum computing, yet the educational infrastructure to produce such talent is still in its initial stages of development [4]. This gap is not just in specialized quantum researchers but extends to a broader range of roles, including engineers, programmers, and educators with a working knowledge of quantum principles as highlighted by September 2022 report by the World Economic Forum (WEF) and IBM committing to skill 30 million people globally by 2020 to help meet the skills gap [5].

The lack of skills workforce in quantum computing has many parallels with what has happened with lack of skilled workforce in cybersecurity today [6]. The problem was identified early, however due to not incorporating cybersecurity in computing curricular has contributed to currently a huge skills gap. CyberSeek, a project supported by the National Initiative for Cybersecurity Education (NICE), a program of the National Institute of Standards and Technology in the U.S. Department of Commerce recently reported that in the U.S. "U.S. the cybersecurity workforce has more than 950,000 workers — with around 465,000 of them yet to be filled" [7, 8]. The initiative, certificate program, degree programs both at the associate, bachelors and master's degrees still to not produce enough cybersecurity professionals. Did NSF/NICE efforts come too late? Are we going to see the same skills gap in the areas of quantum computing?

This paper outlines current efforts in quantum education describes to date and how Saint Martin's Computer Science Department is contributing to these efforts. We have developed a curriculum designed to develop computer science curiosity and interest in quantum computing using the KEEN framework [11] discussed below. We outline strategies to incorporate introductory quantum computing modules into CS curricula, and report how we increased students' quantum curiosity and aptitude, suggesting a positive trend in pursuing gaining more knowledge about quantum computing. This was demonstrated by the student survey thus meeting the quantum education outcomes and research goal as set out for this course.

Current Efforts in Quantum Education

Recognizing this workforce gap, various stakeholders are undertaking efforts to promote quantum education. For example, IBM, a leader in quantum computing research and development, has pledged to upskill 30 million individuals by 2030, with a specific emphasis on quantum computing and cryptography [5, 7]. This pledge significantly impacts education, industry and global research – a win-win. [8]. The White House Office of Science and Technology Policy, along with the U.S. National Science Foundation (NSF), has played a pivotal role in fostering quantum education. They organized summits and discussions bringing together leading educators and professionals creating a Quantum Information Science and Technology (QIST) work force to strategize on future workforce development. The involvement of high-profile governmental entities highlights the national importance placed on quantum education. [9]. These efforts by both private and public sectors reflect a growing recognition of the importance of quantum education and its pivotal role in preparing a skilled workforce for the future. As with cybersecurity initiatives led by NICE and NSF, Quantum educational initiatives need to learn from the failures of preparing cybersecurity workforce [10], adapt well design frameworks and accelerate educational initiatives to bridge the current skills gap and ensuring that the workforce is ready for the challenges and opportunities of the post-quantum era. We propose that there is no need to 'redesign the wheel'.

Incorporating Quantum Computing into CS Curricula

Instruction Modules

The modules were designed to help students develop an entrepreneurial mindset [11]. The entrepreneurial mindset is a broad term for how students grow and change into the computer scientists of the future, with a mindset focused on creating value for society in a broad way. Creating value includes helping students develop character traits that will make them ethical decision makers in the future [12]. To address this goal, the modules were designed to help the students build strong habits and skills about complex issues based on the following:

1. *Curiosity*: This involves instilling a sense of inquisitiveness in students about the ever-evolving world of work, encouraging them to adopt a critical approach, challenging accepted norms and exploring alternative solutions.

Students' curiosity was ignited by explaining the Young's Double Slit Experiment, demonstrating quantum mechanics in action. This hands-on approach in the classroom sparked their inquisitiveness about the peculiar nature of quantum phenomena. Teaching the concept of Circuit Composer and Bloch Sphere create curiosity through visualization utilizing tools demonstrating the multidimensional nature of qubits. This sparked further curiosity about the complex behavior of quantum states. Furthermore, explaining quantum concepts superposition and entanglement with real-life scenarios helped students see the practical applications of these abstract concepts. It nurtures curiosity by, prompting them to question how these principles play out in real-world situations.

The Exploration of Quantum Algorithms and Noise created value in advanced concepts since by delving into advanced topics like quantum noise, Gaussian wave functions, and quantum Fourier Transform (QFT), we can guide students in understanding and applying complex concepts in quantum computing. This not only adds value to their learning experience but also prepares them for tackling real-world quantum computing challenges.

2. *Connections*: Here, the focus is on synthesizing diverse information sources to enhance students' analytical skills. It teaches them to effectively gather, evaluate, and manage information, fostering their ability to make informed decisions [2].

   By explaining quantum gates and providing real-life scenarios students draw connections between the quantum and classical worlds. This approach enhances their analytical skills, enabling them to evaluate and synthesize information from various perspectives.

   We used practical simulation tools like IBM Quantum Simulation to write code and visualize results offered a practical way for students to connect theoretical knowledge with practical applications – this was key to understand quantum mechanics principles like the Heisenberg's Uncertainty Principle.

Creating Value: This component is dedicated to guiding students in identifying and seizing opportunities to generate significant value. Emphasizing perseverance and resilience, it encourages students to embrace exploration, learn from setbacks, and persist in their endeavors [12].

This was accomplished through several different practical modules: (1) Quantum Games Creation: Designing games such as Rolling Dice Competition and Rock-Paper-Scissors, using quantum gates and superposition principles to demonstrate how quantum computing can be applied creatively. This activity shows students how they can generate value through innovative applications of quantum principles. (2) *Hands-On Learning with Quantum Algorithms:* Advanced concepts like Shor's and Grover's algorithms, quantum noise, and teleportation, are taught through hands on exercises using IBM's simulation tools. They learn to monitor, optimize quantum circuits, and apply algorithms, equipping them with the exploring skills necessary for the field.

The course learning outcomes designed around the 3C's discussed above:

- LO1: Understand quantum physics fundamentals and their experimental demonstrations.
- LO2: Understand quantum gates and their applications, enhancing understanding through real-world analogies.
- LO3: Gain proficiency in quantum programming using simulations, applying concepts in a practical setting.
- LO4: Apply quantum principles in designing innovative games.
- LO5: Understand how complex quantum algorithms and concepts, are used to solve problems and applied in the real-world scenarios.
- LO6: Visualize quantum states and circuits using advanced tools, facilitating a deeper understanding of quantum mechanics.
- LO7: Explore research in advanced quantum computing concepts and algorithms and how they are applied in practical scenarios. Designed to gain a comprehensive understanding.

Integrating quantum computing into computer science (CS) curricula involves a strategic approach to ensure that students receive a foundational understanding of quantum principles alongside classical computing concepts. Using the three C's and learning outcomes outlined above, the following modules were delivered in the Introduction to Quantum Computing utilizing an interdisciplinary approach and project-based learning. Two courses Introductions to Quantum Computing (QC) and Quantum Computing II were delivered in fall 2023 and Spring 2024. Due to restricted length of this paper we outline the curriculum for Introduction to QC and present the data collected. Since the same students were in QC II, there was no variance in the data collected. QCII was offered due to the sheer interest from the students in QCI

The research goal of the project was to determine if a structured module in a computer science course could help students enhance and practice skills for discussing new technologies and show interests in pursuing learning about quantum computing after the class. This module is also part of a larger effort at Saint Martin's university to embed the entrepreneurial mindset across the curriculum.

Course Modules

The course modules for "Quantum Computing I & II" are designed to incrementally build a student's understanding and skills in quantum computing. Each module is structured to achieve specific learning objectives:

Quantum Computing I:

- **Fundamentals of Quantum Physics:** Introducing the basic principles of quantum mechanics that underpin quantum computing, such as superposition and entanglement.

- **Quantum Computing Principles:** Covering the theoretical foundations and the differences between classical and quantum computing.
- **Quantum Programming with Python:** Teaching students to implement quantum algorithms using Python, making the course accessible to those with a background in conventional programming.
- **Practical Applications:** Exploring how quantum computing can be applied in various fields, thereby contextualizing its importance and potential impact.
- **Hands-on Experience:** Using tools like IBM's Qiskit framework to create and visualize quantum circuits, providing practical skills in quantum programming.
- **Real-world Problem Solving:** Applying quantum algorithms to solve problems, demonstrating the practical utility of quantum computing skills.

During the quantum computing course, following the lectures, students were required to complete a set of practical labs as follows:

1. Create a quantum circuit with different numbers of qubits and classical bits, applying different quantum gates such as Hadamard, C-NOT, Pauli-X and Y and Z, Toffoli, S, and T-gates and analyzing the results.
2. Create Quantum-Dice game using Qiskit applying Hadamard gate to create a superposition state.
3. Create a Quantum Coin-Flip game, Quantum Tic-Tac-Toe, and Quantum Rock-Paper Scissors game using different quantum gates. Students should use IBM Quantum Simulator
4. Create quantum search Algorithm using simple Grover Search Algorithm and analyzing the results
5. Using IBM Qiskit, implement QFT Algorithm on different states such as a five-qubit state of ‘10110’
6. Using the Provider Object, find how many quantum systems do they have access to for 5 or more qubits.
7. Using IBM Simulator, create and draw a schedule with Gaussian Waveform from the Pulse library.

Research Project(s): Exploring Enhanced Security in Communications using Quantum Electron Spin and Quantum Angular Momentum.

The project stimulated In-Depth Inquiry into Quantum Mechanics and it focus on exploring quantum electron spin and quantum angular momentum, which helped students to have developed a deeper curiosity and understanding about the fundamental particles and their behavior in quantum states. This topic, being at the core of quantum mechanics, offers a rich ground for inquiry and discovery. This type of research project encouraged students to delve beyond textbook knowledge, fostering a culture of exploration and inquisitiveness about cutting-edge quantum technologies and their implications in communication security. It was designed to help students link complex quantum mechanical concepts to the practical domain of communication security. By focusing on communication security through quantum means, the project highlights the significant value quantum computing brings to enhancing cybersecurity as one of the ‘fears’ the media continues to project fears of securing our data and financial domains in a post-quantum world. These skills are invaluable in a field that is continually evolving and has a high potential for groundbreaking discoveries.

Educational Modules and Open-Source Tools

Open-Sources	Topics	Modules	Note
IBM Qiskit	Basic Quantum information • Single Systems • Multiple Systems • Quantum Circuits • Quantum Gates • Quantum Entanglement Quantum Algorithmic Foundation • Quantum Query Algorithms • Phase-Estimation • Grover's Algorithm Qiskit Implementation Introduction to Quantum Cryptography • Hash Functions • Symmetric and Asymmetric Key • Quantum-Safe Cryptography Quantum Information • Density Matrices • Bloch Sphere • Multiple Systems and Reduced States	Weeks 1 - 8	Class lectures and Assignments, and Programming Excercises https://learning.quantum.ibm.com/catalog/courses
IBM Quantum Composer and Simulator	• Build your Ciruits • Apply your Gates • Analyze Q-Sphere	Weeks 3 , 5 & 6	Hands-on Practices https://quantum.ibm.com/composer
IBM Labs	• Jupyter Lab • Matplotlib • NumPy • SymPy	Weeks 3 - 7	Hands-on Practices https://lab.quantum.ibm.com/
Brilliant.org	• Quantum Objects • Quantum Computing • Qubit Playground • Superpositions • Quantum Communication • Quantum Teleportation	Weeks 1 - 7	Assignments https://brilliant.org/quantum-computing

1. **IBM Qiskit:**
Qiskit is an open-source quantum computing software development framework by IBM. It allows users to work with quantum circuits and algorithms on simulated quantum machines. Qiskit was used in the course to enable students to implement quantum algorithms and explore quantum computing principles using a hands on approach in an easy to implement and use framework.

2. IBM Quantum Composer and Simulator:
We used the IBM Quantum Composer as a graphical tool for building and visualizing quantum circuits, and the IBM Quantum Simulator as a platform for simulating quantum circuits on a classical computer. Students learned how these tools were integrated into laboratory exercises and how they are used in projects. This enables students to visually construct quantum circuits and simulate their behavior, thereby solidifying their understanding of quantum mechanics. Image 1 below shows the IBM Qiskit Composer and Simulator. The Q-sphere (bottom right), shows the 3D state of the qubit(s) and how it changes by applying different Gates (top left depicts the Gates)

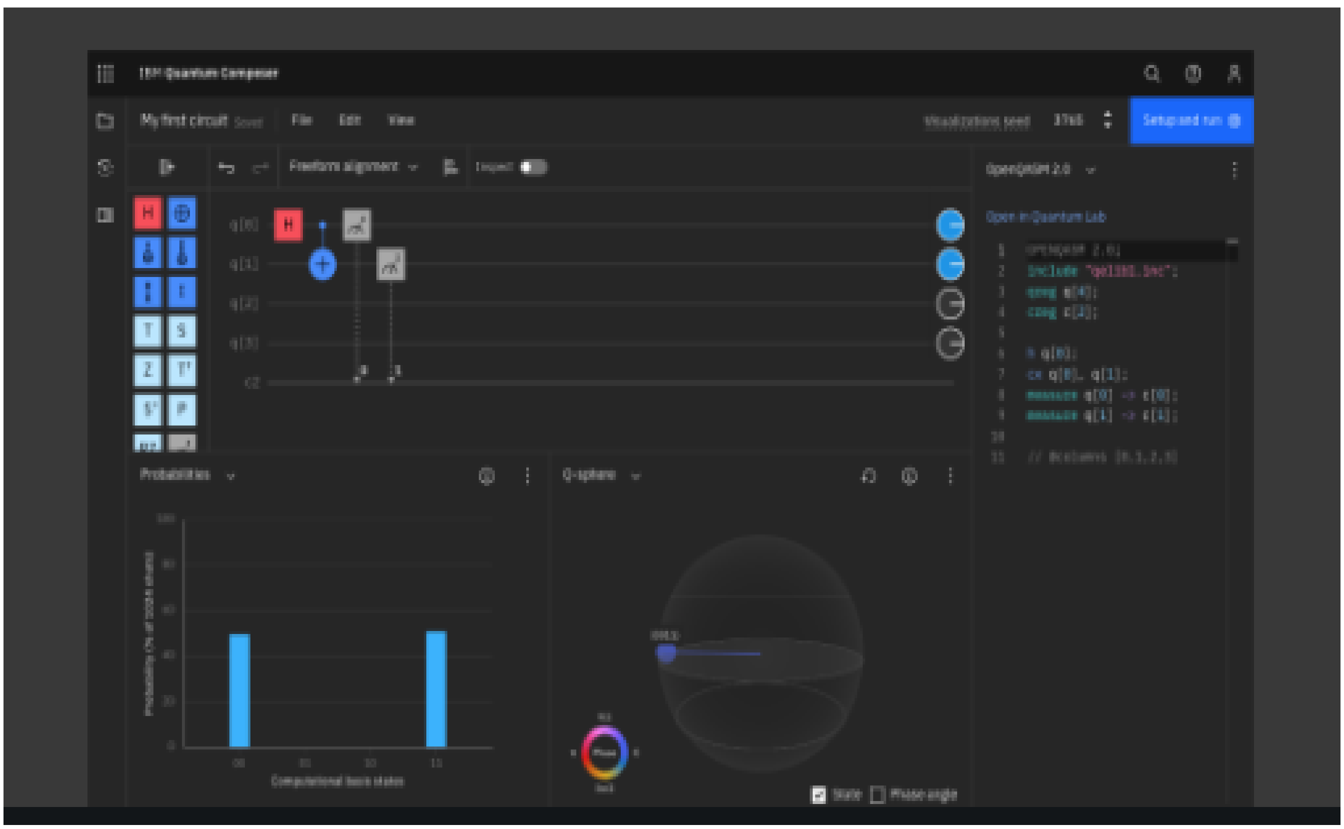


Image 1: IBM Quantum composer and simulator

3. IBM Labs:
IBM Labs is a platform that provides online experiments and learning resources on quantum computing. Students used IBM labs were utilized for advanced experiments or demonstrations, which provided students with exposure to cutting-edge research and applications in quantum computing. Image 2 below shows the IBM Qiskit Lab Launcher; it’s part of the Qiskit Lab available options based on the subject we were studying. Students selected different launchers to

write the quantum code and then they were able to visualize it. We used the “Console” Python, to write and run our codes.

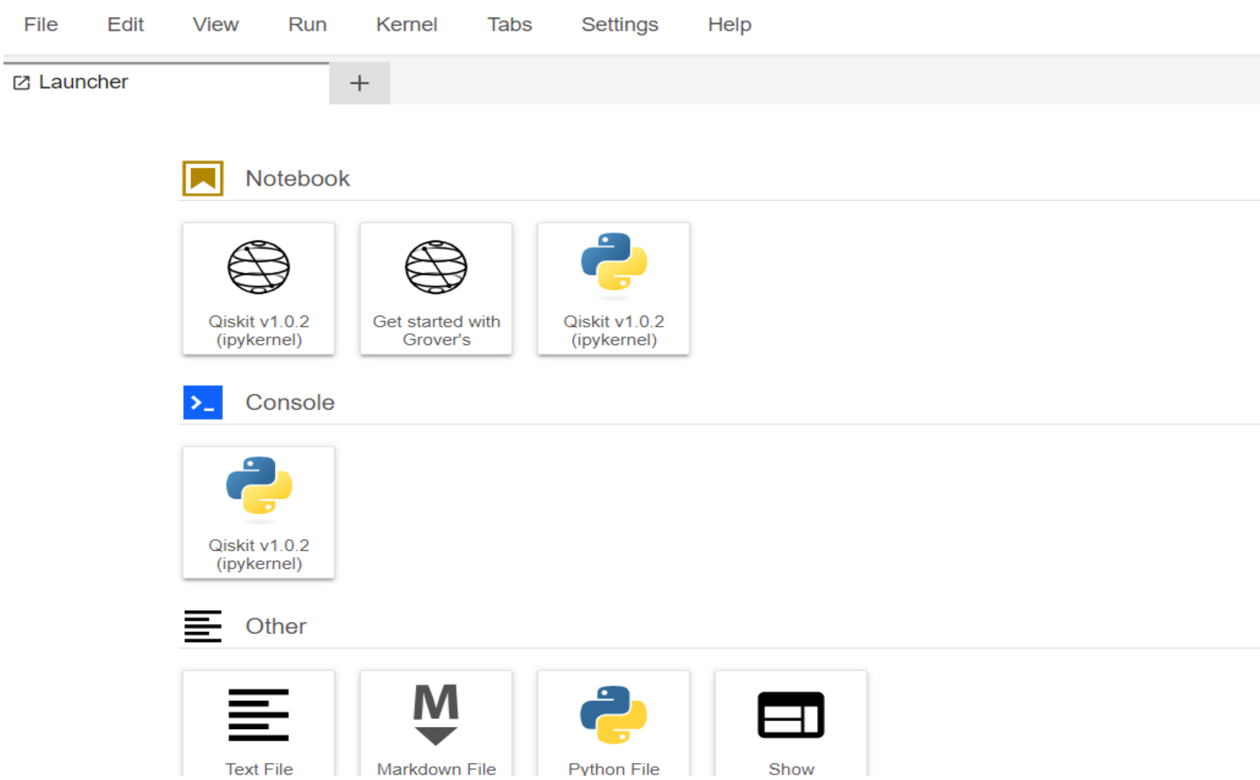


Image 2: IBM Qiskit Lab Launcher

4. Brilliant.org - Quantum Computing and Algorithms:
Brilliant's course platform offers interactive learning experiences in quantum computing and algorithms. The instructor created weekly quantum computing assignments for the students to work on (Image 3). Each gray puzzle must be completed in order to go to the next step. This platform was used to help students understand complex quantum concepts through engaging, simple hands-on ‘fun’ activities. The projects were game-like assignments which students enjoyed working discussing and sharing their experience in rich discussions.

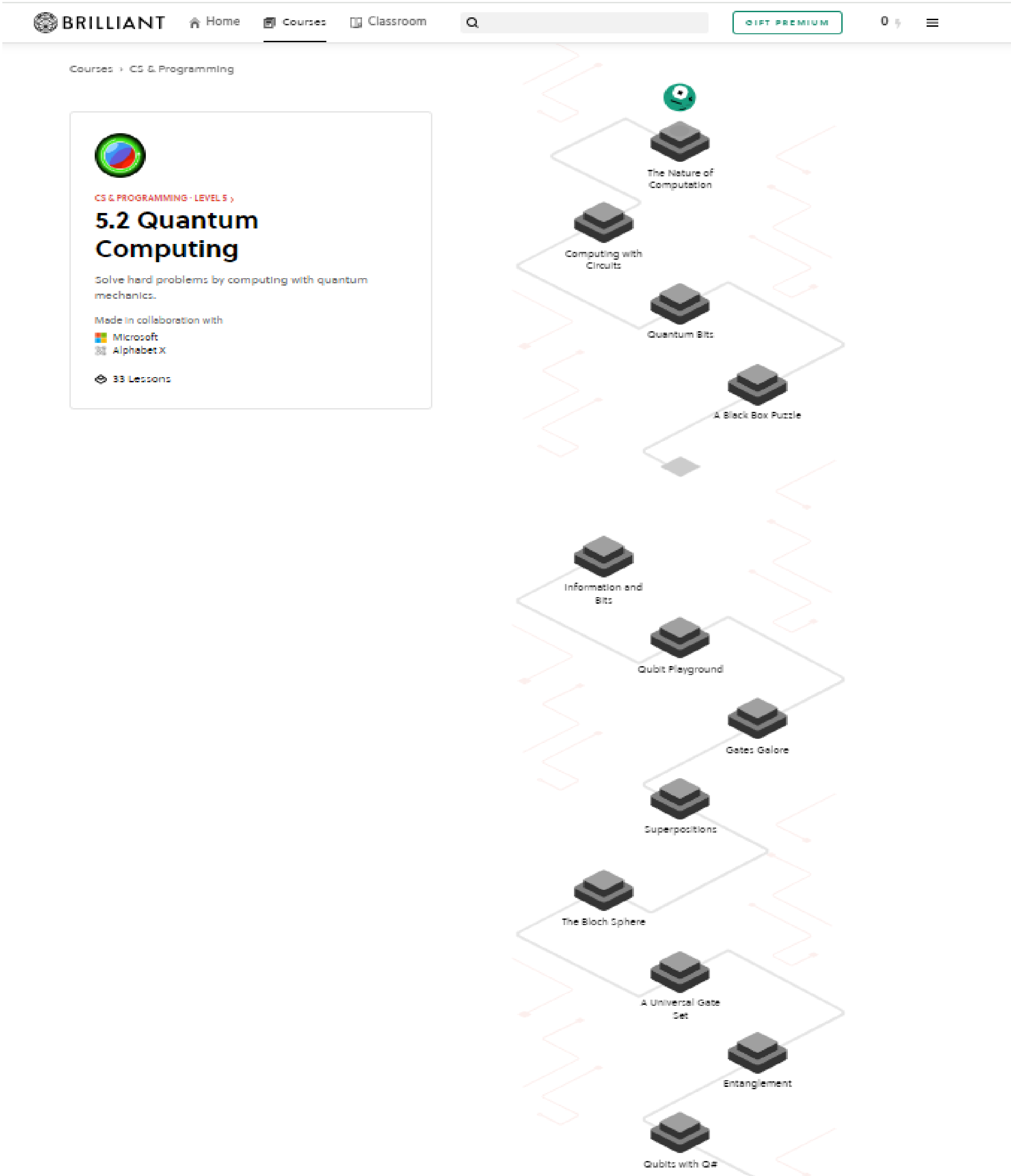


Image 3: An example of Brilliant's quantum-path. Each button will be unlocked by completing the previous step**.**

Moreover, in addition to these tools, lectures were provided to ensure students comprehended both theory and practice. This approach was pivotal to the overall teaching methodology of each module. The hands-on experience served to directly connect theoretical knowledge with practical application in the field of quantum computing.

Student Survey Assessment

Participants: The student participants were all juniors and seniors in computer science. 9 students were enrolled in QC1 and 7 in QC2. We were most interested in the data from Q4 (below): '*To what extent will you continue to pursue gaining more knowledge about Quantum Computing*? To investigate if students' interest and curiosity in quantum concepts, as well as their eagerness to further explore the realm of quantum computing was achieved by the set outcomes. It is important to note that QCII was offered due to students requesting another course to 'learn more', which demonstrated the impact the first course had as supported by the data from the 4th Question.

Assessment Methods: To determine if students had met the learning objectives the module was designed to address, a student survey was delivered to assess specific learning objectives. The following four questions were asked in each class:

1. To what extent has your ability to develop an understanding of quantum computing increased during this class?
2. To what extent has your ability to observe trends about the changing world with a future-focused orientation/perspective increased during this class?
3. To what extent has your ability to consider a solving problem from multiple fields, viewpoints/experiences increased during this class?
4. To what extent will you continue to pursue gaining more knowledge about Quantum Computing?

Research Question

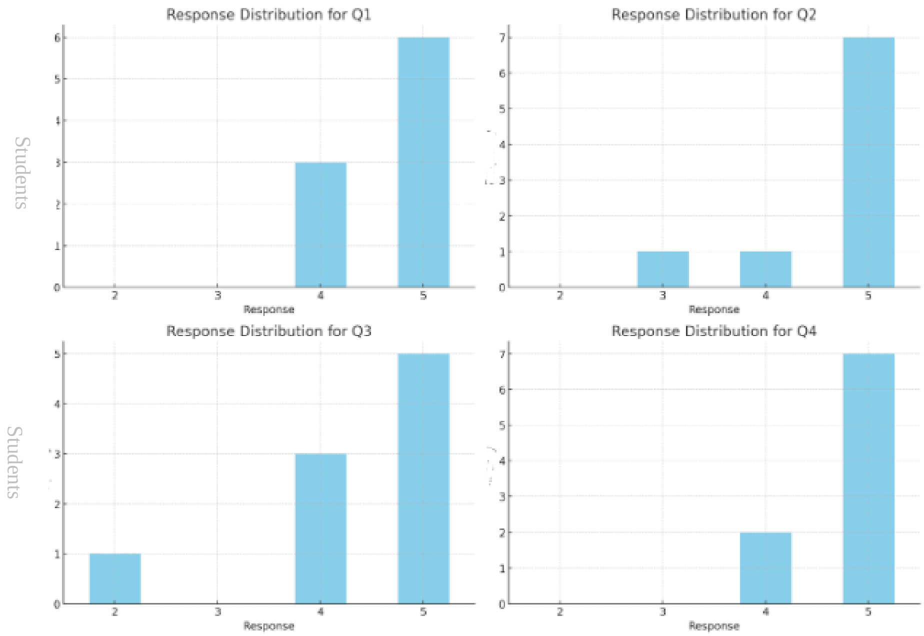
These findings strongly endorse the achievement of our educational objectives with the outcomes and comments in Question 4 (Table 1) showing mean 4.78 - highest for all four questions. The analysis of these courses indicates a positive trend in quantum education outcomes, demonstrating the potential effectiveness of a well-structured and comprehensive quantum computing curriculum. The insights gained from these courses can guide future initiatives and improvements in quantum education, contributing to the development of a skilled workforce in this rapidly evolving field.

Feedback for Improvement: While the overall feedback was positive, students also provided constructive feedback suggesting areas for improvement, such as the need for more real-world examples and case studies, and more interactive learning components. This need was demonstrated with the lowest score for Q3 (Table 1).

Table 1. Summary of the Likert question results in the student survey.

Objective	*n*	*Mean*
Developing an understanding of quantum computing increased during the class	9	4.67
Did the ability to observe trends about the changing world with a future-focused orientation/perspective increased during this class?	9	4.67
Did the ability to consider a solving problem from multiple fields, viewpoints/experiences **increase during this class**	9	4.33
To what extent will you continue to pursue gaining more knowledge about Quantum Computing?	9	4.78

Figures 1-4 . Student responses Questions 1-4 as summarized in Table 1, above. No. of students are on the y-axis, response rating on x axis.



Student Open Ended questions/comments and Trends

Q1 Open ended: Describe a specific example of how your ability to observe trends about the changing world with a future-focused orientation/perspective increased in this class.

- "I Learned a lot about what quantum computing can do and how it will affect our daily lives. It was also interesting learning how to actually code quantum computing with our normal computers which I didn't know was possible."
- "The whole concept of quantum computing was new and fascinating. By the end of the first class, I had come to the realization that quantum computing today is what personal computing was in the 1980's and I was excited to learn about a new technology. I am hopeful that quantum computing will be one of the classes that will give me a competitive edge when it comes to future employment."
- "The topic of Quantum Computing was something that I did not expect to have covered during my time at the university. The topic in itself was something new and exciting. The main things that was interesting to me was having the hands-on experience with creating quantum circuits with gates, measuring, and seeing the results."

Q2 Open ended: Describe a specific example of how your ability to observe trends about the changing world with a future-focused orientation/perspective increased in this class

- "I think learning about the different things going on in technology world has helped me to be more observant of advancements in my field'"
- "Every day during the semester, our professor introduced relevant topics and technologies that will implement the use of Quantum Computing. This led to a curiosity and further research which made me aware of the future implementations."
- "My curiosity specifically led me to observe the impact it will hold over in the field of cybersecurity"
- "The whole class was new to me because I only know just a micro amount about coding. In this class I learned a lot about what a hadamard gate, Pauli-x, y,z gates and controlled

gate and how to use them. While also learning so much on what quantum physics was too that was completely new to me as well."

- "What particles do and how they change based on how you measure them. Even learn how to make a rock, paper, scissor game and dice game so fun. Learned so much from Professor Bahadori. Thank you so much."
- "The trends of the world are changing more towards high tech coding and A.I. along with quantum coding that takes a thousand years of math and does it within a split second. Was really amazing learning about how google is using an A.I. on a human and how the military is also using A.I. to find a target and destroy it and is still a work in progress the news which were applicable."

Q3 Open ended: To what extent has your ability to consider a solving problem from multiple fields, viewpoints/experiences increased during this class?

- "I learned how quantum computing is used in finance and how quantum helps with different trends in the data. I had not thought of quantum being used this way."
- "Quantum computing takes a level of understanding of Python, and how computer languages work. And it will take an understanding of how physics and electronics gate theory works as well. I witnessed my classmates struggle with the concepts of gates and what they do when gates interacted with qubits."
- "The one thing I realized during this course, is that everything that was covered in my previous semesters in other courses, somehow was connected to the topic being covered."
- "My ability to consider a problem from multiple viewpoints in this class happened when I saw that there are multiple ways to create gates for a specific problem"

Q4 To what extent will you continue to pursue gaining more knowledge about Quantum Computing?

- "This class was very eye-opening. I will continue to learn more about quantum computing by reading about it through news articles and scholarly journals as they come up."
- "I subscribed to and read quantum computing newsletters. I'm interested in learning about quantum physics to better understand quantum computing. If I weren't graduating soon, I'd be signing up for more quantum computing courses for my degree program."
- "I will definitely be continuing to learn more about Quantum Computing. Even when I'm graduating, I will definitely continue to self-learn / self-teach myself about it."
- "Taking this class made me very interested in this topic and I hope I will be able to pursue this later on in my career"
- "I am excited to attend quantum computing II in the fall. As stated above quantum computing is the future of computer science and by extension the future of information technology. Even if quantum computing was not available in the fall, I would look for other resources on the subject"
- "The materials covered during this course has opened a door that has led me to being curious on all things that might deal with quantum computing. I want to understand it further and will continue to review concepts and fundamentals with different resources."
- "I plan to continue messing around in IBM Quantum Lab over the summer and learn how to apply this knowledge to quantum computing as a whole."

- “I would take more courses on quantum coding because you’re learning 4 subjects in one that’s fun as it is difficult.”

Student Survey Assessment

In general, the students ranked the objectives well. The highest values were given to considering pursuing learning about quantum computing, indicating the course has have been successful meeting our core objective to pique curiosity and interest in quantum computing to pursue more knowledge and exploring future opportunities.

Student Engagement and Interest: There has been a noticeable increase in student engagement and interest in quantum computing. This is evident from class participation, project submissions, and a request for the faculty to offer an advanced course(s) resulting in QC II being offered.

Survey Results: Student survey results have shown a substantial increase in students' quantum curiosity and aptitude. Key findings include:

- *Improved Understanding:* Students reported a better understanding of complex quantum concepts after taking these courses.
- *Practical Skills:* Hands-on exercises and projects were particularly effective in enhancing students' practical skills in quantum computing.
- *Career Interest:* A significant number of students expressed increased interest in pursuing careers in quantum computing or related fields supporting the research goals.

Conclusions

This course was designed for computer science students to foster skills and an entrepreneurial mindset specific to quantum computing. Student feedback indicates that the modules were particularly effective in teaching them to approach problems from multiple perspectives, an essential skill for developing a comprehensive mindset in the field. Our analysis of the quantum computing courses "Introduction to Quantum Computing," and "Quantum Computing II" has revealed significant progress in student engagement and understanding. The positive response and increased curiosity among students underscore the effectiveness of the curriculum design and the pedagogical approaches employed. These courses not only impart fundamental knowledge and skills in quantum computing but also stimulate students' interest in further gaining more knowledge exploring opportunities in this emerging field.

This paper also analyzes the current state and future potential of quantum computing education, focusing on initiatives by public and private sectors to address the educational gap in this rapidly evolving field. The instructor shared the open-source resources encouraging others to explore them and weave them into their curriculum. Furthermore, encouraged by the curriculum's initial success, the instructors plans to devise a framework modeled after the NICE Workforce model for cybersecurity education. This new framework aims to bolster industry-academia collaboration, enhance educator training, improve the availability of learning resources, encourage cross-disciplinary study, integrate project-based learning, and nurture a supportive community of quantum educators and learners.

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