BOARD # 68: Exploring the Impact of a Simulation-Based Learning Tool on Undergraduate Quantum Computing Education

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Abstract

As quantum computing (QC) technologies continue to advance, there is an increasing demand for a workforce skilled in QC. Higher education plays a critical role in preparing students with the foundational knowledge and specialized skills required for careers in quantum research, development, and application. While a few studies have introduced QC to high school students or computer science majors, there is limited focus on students from diverse academic backgrounds. Existing research has primarily shared instructors' experiences and efforts in teaching quantum computing in higher education, but there is a notable lack of studies exploring ways to enhance QC instruction and examining students' learning and attitudes. This study introduces the Spin-Quantum Gate Lab, a tool designed to enable undergraduate students to learn quantum computing concepts through simulations. The tool is grounded in multimedia-based learning (MBL) and simulation-based learning (SBL) theories, incorporating MBL materials, SBL tools, and hands-on programming exercises to enhance QC education. To evaluate the tool's impact on students' learning outcomes and attitudes, 19 undergraduate students from diverse majors at a public university participated in a two-week quantum information science course using the tool. Data collection included pre- and post-surveys with knowledge tests, attitude questionnaires, and post-only engagement and usability surveys, alongside open-ended questions exploring students' feedback on the lab. The results demonstrated significant improvements in students' quantum computing knowledge ($p < .001$), medium-to-high engagement and perceived usability scores ($M = 3.90, SD = 1.06$), and no significant changes in attitude. This study introduces an innovative learning tool for undergraduate quantum computing education and provides empirical evidence supporting the effectiveness of the tool in enhancing QC learning.

1 Introduction

Quantum computing (QC), or Quantum Information Science and Technology (QIST), is an emerging field grounded in the principles of quantum mechanics, offering the potential to revolutionize industries by addressing complex problems far more efficiently than classical computers [1]. Over the past decade, its growing significance has been underscored by major global initiatives, including the U.S. National Science Foundation's (NSF) Quantum Leap Big Idea, the European Union's Quantum Flagship, and national efforts in China and Japan [2–5]. These initiatives aim to advance the understanding and application of quantum phenomena, fostering interdisciplinary research and enabling transformative breakthroughs in quantum systems, materials, and communication technologies [6].

As quantum technologies continue to evolve, the demand for a quantum-proficient workforce is accelerating. Higher education plays a critical role in equipping students with foundational knowledge and specialized skills for careers in quantum research, development, and application [7, 8]. However, QC education in higher education remains in its infancy, with many programs still exploring effective ways to integrate QC into existing curricula. Industry-driven initiatives, such as IBM's Quantum Experience[1] and Google's Cirq[2], have put efforts in advancing QC accessibility, but these platforms are often designed for experts or engineering students, leaving a substantial gap for students from entry stage.

Recent years, researchers have focused on develop various educational technologies and pedagogical approaches to support QC instruction. For instance, one study employed a design-based research approach to teach intermediate-level undergraduate quantum mechanics through drawing and simulations [9], while another introduced an online QC course requiring minimal technical prerequisites [10]. Visualization tools are frequently utilized to illustrate complex quantum phenomena, aiding students in understanding abstract concepts [9, 11, 12]. Additionally, efforts have been made to incorporate QC education into STEM curricula [13–15]. Despite these initial explorations, QC education still faces significant challenges, particularly in ensuring accessibility for students from diverse academic disciplines and providing sufficient learning resources. A review of the QC education literature highlights the scarcity of resources and comprehensive curricula, emphasizing the need for effective pedagogical strategies and tools [16]. As QC encompasses nearly all domains of science and engineering—drawing from advances in physics, materials science, computer science, mathematics, and engineering [6], addressing these challenges requires enhanced collaboration among stakeholders. Researchers have also underscored the importance of evaluating how QC courses impact students' self-efficacy, interest, identity development, and sense of recognition within the QC education community [17–19]. However, most recent studies have primarily focused on curriculum design or technology development (e.g., [9, 11, 20]), with limited empirical research conducted (e.g., [10, 12, 14]). These studies often provide only descriptive results without reporting significant learning outcomes (see Table 1).

In this study, we aim to address the limitations of existing QC educational tools by designing and developing a multimedia- and simulation-based learning tool, the Spin-Quantum Gate Lab, which integrates both software and hardware aspects to enhance QC learning. Specifically, our study seeks to (1) provide an intuitive and accessible learning environment for students from diverse academic backgrounds, (2) emphasize hands-on learning through a ”learning-by-doing” approach that combines Multimedia-Based Learning (MBL) and Simulation-Based Learning (SBL), and (3) bridge the gap between QC hardware and software instruction, which has been largely overlooked in prior research.

To evaluate the effectiveness of this tool, we conducted a mixed-methods pilot study with 19 undergraduate students at a public university, examining its impact on knowledge acquisition, attitudes toward QC, and perceived usability. We hypothesize that (H1) students using this tool

[1] https://quantum.ibm.com/
[2] https://quantumai.google/cirq

Table 1: Recent example research studies on quantum computing education.

Literature	Year	Target Population	Approach	Learning Outcome
[12]	2020	High school	Simulation-based labs	Descriptive: QC concepts $\uparrow$; Importance of QC $\downarrow$; Interest in QC learning $\downarrow$
[9]	2020	Undergraduate students	Drawing with simulations	No significant results reported
[20]	2020	Undergraduate major in CS	Software-oriented approach using Q#	No significant results reported
[11]	2021	Users with programming experience	Virtual reality (VR)-based tool for QC programming	No significant results reported
[14]	2021	Undergraduate students	Comparison of Qiskit (IBM), PyQuil (Google), Q# (Microsoft), etc.	Descriptive: QC understanding $\uparrow$; Interest in QC learning $\rightarrow$
[21]	2021	Undergraduate major in engineering	Qiskit (IBM), PyQuil (Google), Q# (Microsoft), etc.	Descriptive: Satisfaction with the course
[10]	2023	Everyone: Massive Open Online Course (MOOC)	Q# (Microsoft)	Descriptive: Retention and difficulty

will show a significant increase in their QC knowledge scores, (H2) students' attitudes toward QC will improve after the intervention, and (H3) the tool will be rated favorably in terms of usability and engagement.

Quantitative data were collected through pre- and post-surveys, including knowledge assessments and attitude questionnaires, while qualitative data were obtained through open-ended feedback questions. The findings indicate significant improvements in students' QC knowledge, with medium-to-high engagement and usability ratings. This study not only introduces an open-access tool to the QC education community but also provides empirical evidence of its effectiveness, highlighting the potential of tailored learning tools to foster a more inclusive and practice-oriented QC education landscape.

2 Related work

3 Quantum computing education

Despite the growing recognition of the strategic importance of QC among educators and policymakers, research on effective strategies for teaching and learning QC remains underdeveloped. While the terms "Quantum Information Science" and "Quantum Computing" were coined decades ago and have garnered significant media attention in recent years, peer-reviewed studies focusing on QC education for undergraduates with diverse academic backgrounds are still limited.

Several researchers have explored various approaches to QC education, with some promising yet context-specific findings. For instance, Hughes et al. [12] introduced a QC course aimed at bridging the gap between popular science articles and advanced undergraduate textbooks through interactive problem sets and simulation-based labs for active learning. However, their target audience consisted primarily of high school students. Similarly, Uhlig et al. [13] reported on a group project in a cybersecurity course that sparked significant interest in QC among graduate students, motivating them to delve deeper into this complex subject.

Other studies have focused on adapting QC education for undergraduate students without a physics background. Carrascal et al. [14] demonstrated the effectiveness of using computer programming, including quantum simulators, circuit testing, and real quantum computer programming, to teach QC concepts. Additionally, Temporão et al. [22] proposed that QC could serve as a gateway to quantum physics for undergraduates, leveraging a blended learning approach with IBM's Qiskit framework. Gatti and Sotelo [21] introduced a curriculum incorporating logic and programming skills in QC using Q# and the Microsoft Quantum Network, effectively engaging undergraduate engineering students. Similarly, Mykhailova and Svore [20] highlighted the success of software-driven approaches that included programming exercises and final projects, demonstrating the positive impact of such methods on undergraduate learning outcomes.

While simulation tools like IBM Qiskit [23] and Google Cirq [24] are widely used in QC education, they come with notable limitations. These tools primarily emphasize programming for cloud-based QC and simulators, which can enhance students' understanding of quantum mechanics and algorithms [9, 25]. However, their applicability often falls short for students in disciplines such as chemistry, materials science, and electrical engineering, where a deeper understanding of hardware operation principles is crucial [26, 27]. A review concluded that QC technologies show promise in achieving results beyond traditional computing methods, but more research is needed to address open problems and advance the field [28].

Moreover, the existing body of literature has largely concentrated on the "software" aspects of QC education, such as quantum theoretical foundations, algorithms, programming, and modeling. In contrast, fewer studies have addressed the "hardware" components, such as quantum technology implementations involving materials, devices, circuits, and practical systems. This gap leaves critical aspects of QC education underexplored. Furthermore, many studies that identify their target student populations focus on physics majors, computer science students, or high school learners [12, 15, 16, 29]. These studies often lack comprehensive data on students' learning gains, attitude changes, and feedback, instead emphasizing instructors' personal reflections and lessons learned in teaching quantum concepts [14, 29].

This study aims to address the aforementioned challenges by designing and developing a simulation tool for higher education. While building on prior research that utilizes simulations and visualization techniques for teaching quantum computing (QC), this study distinguishes itself by integrating both software and hardware aspects. Furthermore, it not only introduces an open-access tool but also provides empirical evidence on its impact on students' learning outcomes. The tool is designed to support diverse learners, regardless of their prior experience with QC.

3.1 Theoretical foundation

The design of the learning technology and instruction for the QC course is grounded in the theoretical framework of cognitive constructivism. Cognitive constructivism, a branch of constructivism, posits that learning occurs as learners actively construct their understanding of the world through experience [30]. This theory emphasizes the role of individual experiences and hands-on activities in shaping cognitive mental models of the world [31]. By engaging in experiential learning or "learning by doing" [32], students form mental representations that help them grasp complex concepts. Given the abstract nature of QC [11, 33], cognitive constructivism [34] provides a strong rationale for the course design. Quantum mechanics requires learners to build new mental models to understand how phenomena at the quantum level differ from classical physics [10, 13]. Therefore, helping learners construct accurate mental models of how quantum systems work can be an effective pedagogical strategy for enhancing their understanding of QC.

In alignment with this theoretical foundation, we adopted several pedagogical strategies—multimedia-based learning (MBL) [35], simulation-based learning (SBL) [36], and experiential learning [37]—to foster hands-on, interactive experiences in QC education.

The MBL materials are carefully designed to include most important and essential physical concepts, selected topics on hardware realization of QC, as well as examples of most important quantum algorithms, a total of six key concepts covered. The design of the video and animation contents followed five principles, as proposed by Betrancourt's work [38]: (1) apprehension principle, (2) congruence principle, (3) interactivity principle, (4) attention-guiding principle, (5) flexibility principle. Taking the quantum tunneling Animation as an example, to provide a graphic depiction of tunneling behavior, the apprehension principle was implemented by following the traditional representation of quantum tunneling. As the barrier thickness became closer to the size of the electron wavelength, the congruence principle made the cause-and-effect link clearer, assisting students in building a functional mental model of quantum interference. The interactivity principle allowed students to interactively change parameters such as the thickness and height of the quantum tunneling barrier, enhancing their understanding of how these parameters influence tunneling. The attention-guiding principle emphasized using deliberate verbal commentary to direct students' attention to the crucial aspects of the quantum tunneling animation. Lastly, the flexibility principle included an option to initiate the quantum tunneling animation within a static image, accompanied by the relevant background information.

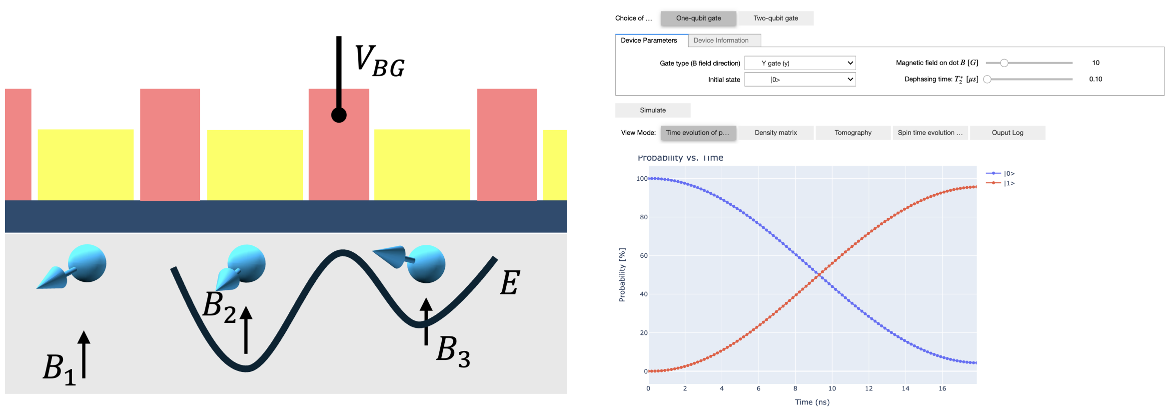
The functionalities of the simulation tool developed to enhance SBL in QC. These tools are designed to facilitate learning in five key categories that are beneficial to SBL in QC: providing background information, helping learners make hypotheses, conducting experiments, interpreting data, and regulating the learning process [39, 40]. To provide background knowledge, the tool offers detailed descriptions and interactive activities. It also includes diagrams to help learners formulate hypotheses about quantum operations and how varying design parameters might affect outcomes. To aid in conducting experiments, the tool comes equipped with a variety of pre-set quantum hardware parameters, alongside a feature that reveals the physical meaning of each parameter as the learner interacts with the tool. Additionally, it facilitates data interpretation through interactive visualizations and animations that demonstrate qubit evolution. Lastly, the tool supports the regulation of the learning process by incorporating pre-simulation quizzes, a step-by-step simulation guide, and tailored homework for self-assessment.

Hands-on or experiential learning promotes trial and error, hence learning from mistakes through self- correction, thereby enhancing and accelerating the learning process itself. Experiential Learning Theory [37] defines hands-on learning as a cycle composed of four elements: (1) concrete experience (i.e., doing or having an experience); (2) reflective observation (i.e., reviewing the experience); (3) abstract conceptualization (i.e., concluding and learning from experience); (4) active experimentation (i.e., trying out what has been learned). For concrete experience, students start with a quantum program that is either functionally incorrect and/or functionally incomplete, run the program and record their observations, which forms the initial concrete experience. For reflective observation, students analyze the outcome of the incorrect/incomplete quantum program. For abstract conceptualization, students identify code structure/statements that lead to incorrect/incomplete behavior, for active experimentation, students fix code structure/statements that lead to incorrect/incomplete behavior.

4 Methods

4.1 Spin-Quantum Gate Lab

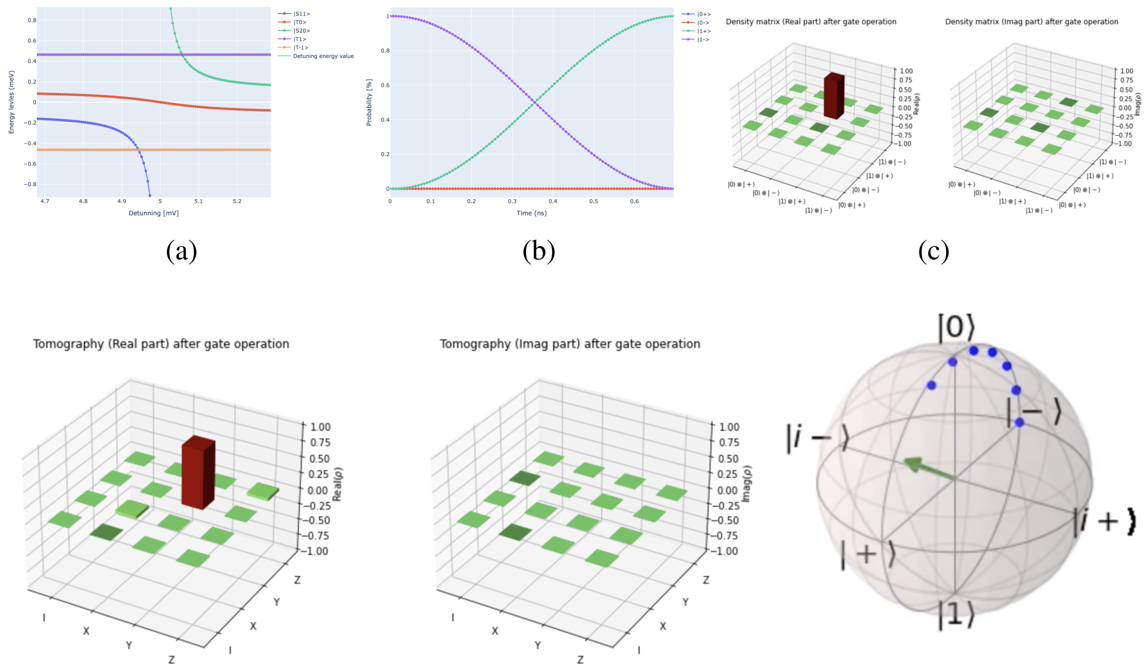
The Spin-Quantum Gate Lab is an interactive simulation tool designed to provide hands-on experience with quantum gate operations, particularly in the context of silicon-based spin qubits. This tool was developed to make the complex field of QC more accessible to undergraduate students by linking theoretical concepts with practical experimentation. The tool simulates the behavior of single-qubit rotational gates and two-qubit controlled-phase (CPhase) gates, which are shown in Figure 1a. These simulations are essential for understanding the foundational operations of QC, as they form a universal gate set. Figure 1b shows the user interface of the tool which allows users to manipulate parameters such as magnetic field values, dephasing times, and initial quantum states, enabling a comprehensive exploration of quantum phenomena. The simulations are based on the Lindblad Master Equation (LME) [41], which accounts for the decoherence effects that occur in quantum systems.



(a) (b)

Figure 1: Spin qubit array and device parameter configuration interface. *Note*: (a) The spin qubit array consists of a single-qubit rotational gate and a two-qubit gate, which together form a universal gate set for QC. The application of a magnetic field induces spin rotation, enabling the implementation of a single-qubit rotational gate. In contrast, applying a voltage to the barrier gate between two spins facilitates the creation of a two-qubit entangling gate. (b) The control panel allows for the configuration of various device parameters, including the initial state, magnetic field strength, and dephasing time, among others.

The tool offers multiple visualization modes to enhance comprehension of quantum systems. The energy levels plot in Figure 2a highlights the variations around the detuning point, illustrating how the quantum system is controlled. The time evolution of probability in Figure 2b reveals how the probabilities of different quantum states evolve, with emphasis on dephasing and the gradual loss of pure states due to decoherence. The density matrix in Figure 2c provides a detailed representation of the quantum state, encompassing both pure and mixed states while demonstrating the effects of decoherence. Quantum tomography in Figure 2d enables comprehensive characterization of the quantum state through measurements in different bases, such as Pauli matrices, offering deeper insights into its properties. Lastly, the spin rotation



(a) (b) (c)

(d) (e)

Figure 2: Visualization of quantum mechanisms through simulation results. *Note*: The tool presents various simulation results to enhance the understanding of latent quantum mechanisms. (a) The relationship between energy levels and detuning energy for the CPhase gate illustrates the gate's operation via manipulation of detuning energy. (b) The time evolution of probability distributions reveals the probability of each state, highlighting the decoherence of pure states over time. (c) The density matrix offers a comprehensive representation of the quantum state, capturing both mixed states and decoherence effects. (d) The quantum state tomography, derived from measurements in the Pauli matrices, provides a detailed visualization of the state. (e) The spin rotation sequence depicts the dynamics of spin rotation under an applied magnetic field, offering valuable insights into the associated physical processes.

sequence in Figure 2e illustrates the dynamics of spin rotation under an applied magnetic field, enhancing the understanding of these quantum processes.

In contrast to previous tools highlighted in [10, 12], which primarily emphasized the software aspects of Quantum Information Science and Technology (QIST) education—such as quantum theoretical foundations, algorithms, programming, and modeling—the Spin-Quantum Gate Lab integrates both these software dimensions and the critical hardware aspects essential to quantum computing (QC) education. This includes, for instance, the implementation of quantum technologies across various levels, from materials and devices to circuits and practical systems. To address the gap in the literature regarding limited studies on students' learning outcomes and feedback, we conducted a classroom experiment utilizing the Spin-Quantum Gate Lab. Furthermore, our study incorporates participants from diverse academic backgrounds, and we systematically analyze their experiences, knowledge acquisition, attitudes, engagement levels, and perceptions of usability following their interaction with the Spin-Quantum Gate Lab.

4.2 Participants

To evaluate the effectiveness of the MBL, SBL, and hands-on programming content, a total of 19 students from a public university in the southern United States participated in this pilot study. The participants predominantly majored in engineering disciplines, including Electrical and Computer Engineering (ECE), Materials Science and Engineering (MSE), Computer Science (CS), Biology and Chemistry. Of the 19 students, six were undergraduates and 13 were graduate students. The gender distribution included 16 male and three female students. In terms of ethnicity, 10 participants identified as Asian, five as White, two as South Asian, one as Black/African American, and one did not report their race. This study received IRB approval from the University of Florida with IRB No. 202200587.

4.3 Procedure

This study consists of three phases. Pre-Intervention phase: Participants voluntarily joined the study. Prior to engaging with the Spin-Quantum Gate Lab to learn QC, students completed a pre-survey designed to assess their background, experience, and prior knowledge. An additional attitude survey was administered to capture their perceptions of QC before the intervention. Intervention phase: Participants engaged with the Spin-Quantum Gate Lab for a total of approximately two hours every two weeks, over a period of two weeks. This phase was designed to offer a blended learning experience that combined hands-on interaction with the simulation tool and teacher-led instruction to deepen the participants' understanding of QC concepts. The Spin-Quantum Gate Lab was integrated into the curriculum with a focus on scaffolding the students' learning process. Each session began with a brief instructional segment where the teacher introduced key concepts such as single-qubit gates, two-qubit gates, and quantum entanglement. Following this, the students were guided through step-by-step exercises using simple examples within the lab tool, which helped them apply these theoretical concepts in practice. Post-Intervention phase: Upon completing the intervention, students were asked to fill out a post-survey, which mirrored the pre-survey in evaluating their background, experience, knowledge, and attitudes. Additionally, students completed an engagement and usability questionnaire, along with three open-ended questions.

4.4 Measurements

The participants used the MBL materials and the SBL tool in the same quantum information science course for two weeks. Pre- and post-surveys were administered to collect data. In addition to eight questions about students' background and their QC learning experience, the pre-survey (shown in Table 2) includes five knowledge test questions, such as "*Which of the following can form a universal set of quantum gates?*". The five-point attitude questionnaire, adapted from Hanrahan et al. [42]'s work, consists of seven items that explore students' self-efficacy and identity related to QC. The post-survey retains the knowledge test and attitude questionnaire from the pre-survey and adds a seven-item engagement and usability questionnaire, adapted from Brooke [43]'s study (shown in Table 3). It also includes three open-ended questions, such as "*How did the Spin-Quantum Gate Lab aid your understanding of quantum computing concepts?*" and "*What did you like about the Spin-Quantum Gate Lab?*".

Table 2: Pre and post survey used questions. *Note:* Background questions were open-ended, experience and attitude questions were rated on a five-point scale, and the knowledge test consisted of multiple-choice questions, with correct answers scored as 1 and incorrect answers as 0.

Constructs	Question Number	Question Text
Background	1	What is your full name?
	2	What is your major?
	3	Are you in undergraduate or graduate school?
	4	What year are you?
	5	Please select your gender
	6	Please select your ethnicity/race (select all that apply)
Experience	7	I have experienced quantum computing education before this course.
	8	I have developed an application using quantum computing before this course.
Knowledge test	9	Which of the following can form a universal set of quantum gates?
	10	To realize an X gate on a semiconductor spin qubit, what is the direction of the magnetic field of the control pulse?
	11	If the dephasing time of a quantum gate increases, what is its impact on fidelity?
	12	A semiconductor double quantum dots structure consists of two neighboring quantum dots Q1 and Q2. It can form a two-qubit quantum gate. Which of the following can achieve a two-qubit controlled-phase gate operation?
	13	Which of the following can result in a faster two-qubit quantum gate, which has a smaller gate delay?
Attitude questions	14	I can understand the concepts of quantum mechanics when I read.
	15	I can understand the concepts of quantum computing when I attend a lecture or prime-time meeting.
	16	I can understand how quantum hardware, such as a quantum gate, is realized when I run simulations.
	17	I can understand the physical concepts used in quantum computing.
	18	Working on quantum computing homework (e.g., this course's homework) is stressful for me.
	19	I believe I can use quantum computing in my future career.
	20	I want to pursue a career in quantum computing in the future.

Table 3: Post-survey only questions. *Note:* The post-survey also includes the knowledge test and attitude questions from the pre-survey.

Constructs	Question Number	Question Text
Engagement and usability	1	This course motivated me to pursue a career in quantum computing.
	2	This course has increased my interest in quantum computing.
	3	I enjoyed using the Spin-Quantum Gate Lab to have simulations about semiconductor-based quantum computing.
	4	I can explain the mechanism of semiconductor-spin-based quantum computing using the Spin-Quantum Gate Lab.
	5	The Spin-Quantum Gate Lab helped me understand the concepts of semiconductor-based quantum computing technology.
	6	I would like to use the Spin-Quantum Gate Lab frequently when I study semiconductor-based quantum computing in the future.
	7	I think the Spin-Quantum Gate Lab was easy and intuitive to use.
Open-ended questions	8	How did the Spin-Quantum Gate Lab help with your understanding of quantum computing concepts?
	9	What did you like about the Spin-Quantum Gate Lab?
	10	What did you NOT like about the Spin-Quantum Gate Lab and how would you improve it?

5 Results

5.1 Experience and knowledge

The experience, knowledge and attitude results are in Table 4. Before the intervention, 12 students reported having no or very limited experience with QC education, and 15 out of the 19 students indicated that they had never developed or had very limited experience in developing an application using QC. Out of the 19 students, 14 demonstrated improved learning performance after engaging with the Spin-Quantum Gate Lab. A Wilcoxon signed-rank test was conducted to

Table 4: Experience, knowledge and attitude results. *Note*: SD is Standard Deviation.

		Pre-survey	Post-survey	
Category	Item No.	Mean (SD)	Mean (SD)	Comparison
Experience	7	2.42 (1.53)	/	/
	8	1.44 (1.12)	/	/
Knowledge test	9	0.37 (0.48)	0.47 (0.50)	$p < 0.001$***, Cohen's $d = 0.90$
	10	0.42 (0.49)	0.84 (0.36)	
	11	0.47 (0.50)	0.74 (0.44)	
	12	0.63 (0.48)	0.84 (0.36)	
	13	0.68 (0.47)	0.79 (0.41)	
Attitude	14	3.58 (0.82)	3.89 (0.72)	$p = 0.81$
	15	3.84 (0.93)	3.95 (0.89)	
	16	3.68 (1.08)	3.74 (0.96)	
	17	3.42 (0.99)	3.47 (0.94)	
	18	3 (0)	2.58 (0.94)	
	19	4.26 (0.85)	4.37 (0.74)	
	20	4.10 (0.72)	3.84 (0.93)	

compare the knowledge scores of the students before and after the two-week intervention using the tool. From overall comparison, the results indicated a statistically significant increase in scores from the pre-test ($M = 2.57$, $SD = 1.23$) to the post-test ($M = 3.68$, $SD = 1.17$), with a large effect size (Cohen's $d = 0.90$) and significance at $p < .001$. This suggests a substantial improvement in students' knowledge following the intervention.

We further compared the learning scores of students with different levels of experience. Among students with prior QC experience (n = 7), all demonstrated an increase in their knowledge scores, with an average gain of 1.57. In contrast, students with no or limited experience (n = 12) showed an average increase of 0.83; this indicates that the Spin-Quantum Gate Lab is helpful for both students with or without QC learning experience.

5.2 Attitude

For attitude, the pre-survey shows that the mean values of the seven attitude questions were 3.58, 3.84, 3.68, 3.42, 3.00, 4.26, and 4.11. After the intervention, the average values for the seven questions changed to 3.89, 3.95, 3.74, 3.47, 3.00, 4.37, and 3.84. Although five out of the seven questions (Q14, Q15, Q16, Q17, and Q19, shown in Table 2) showed an increase in score, no significant difference was found in students' attitudes toward QC. For students with different levels of prior experience, both groups showed an increase in attitude scores. Students with prior experience had an average increase of 0.86, while those without experience showed a higher average increase of 1.25.

5.3 Engagement and usability

Shown in Figure 3, the average scores for Q1 to Q7 in Table 3 are 3.89, 4.11, 4.06, 3.26, 3.79, 4.00, and 4.16. The engagement and usability score ($M = 3.90, SD = 0.87$) from the post-survey indicates that students were actively involved in the learning process and found the materials and tools to be user-friendly. Students without prior experience had an average engagement and usability score of 3.68, while those with experience showed a higher average score of 4.26.

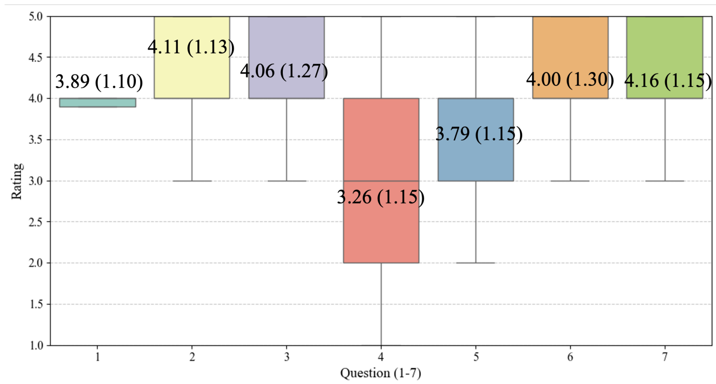


Figure 3: The post-survey engagement and usability results. *Note*: Values like 3.89 (1.10) represent Mean(Standard Deviation).

5.4 Open-ended questions

From the open-ended question Q8 on understanding QC concepts, students emphasized learning by doing, focusing on the role of interactive parameter tuning and visual feedback in enhancing their understanding. They highlighted how simulations provided a hands-on experience. One student noted, "*It (the simulation tool) provided nice visuals to understand the concepts presented in the lectures and class material.*" Another mentioned, "*It helped me understand the relationship between the parameters and increasing fidelity for one- and two-qubit systems.*" Students appreciated the tool's features, often praising its visualization capabilities with comments such as "*nice visuals*" and "*visual simulations*," which helped them grasp complex concepts. Many also mentioned the tool's ease of use, describing it as "*very easy to use*" and "*user-friendly*." Additionally, the quick feedback from simulations was valued, as students found it helpful in understanding quantum gates more effectively. However, some technical issues were reported, including bugs and glitches such as "*small bugs, but they did not distract me,*" and problems with results not refreshing automatically or the result window not changing dynamically. Despite these minor issues, the overall feedback indicates that the proposed MBL material, SBL tool, and hands-on programming content had a positive impact on students' learning of QC.

6 Discussion and conclusion

This study aimed to address several critical gaps in QC education, including (1) providing an accessible learning tool for students from diverse backgrounds, (2) integrating both software and hardware aspects of QC, and (3) leveraging learning-by-doing pedagogies to enhance student engagement. Our findings support the first objective, as the tool was well-received by students with varied prior experience in QC. The second objective—bridging the gap between hardware and software learning—was partially achieved, as students found the tool useful for understanding QC concepts, though the impact of hardware-specific features remains an area for further investigation. Lastly, our study reinforces the efficacy of learning-by-doing approaches, aligning with research demonstrating that active, hands-on experiences contribute to knowledge retention in complex technical domains [14, 28].

The findings from this study demonstrate the effectiveness of the MBL and SBL tool in enhancing students' understanding of QC. Consistent with prior research highlighting the benefits of interactive learning environments in technical education [12, 20], our results show a significant improvement in students' QC knowledge following the intervention. The increase in knowledge scores from the pre-test to the post-test ($M = 2.57$ to $M = 3.68, p < .001$), with a large effect size (Cohen's d = 0.90), underscores the impact of the tool in facilitating deeper conceptual understanding. Despite the improvement in knowledge acquisition, there was no significant shift in students' attitudes toward QC. This suggests that while MBL and SBL tools enhance cognitive understanding, they may need to be supplemented with additional instructional strategies to influence affective factors such as interest, self-efficacy, and career aspirations. Previous research suggests that attitudes toward highly specialized technical fields often require extended exposure and real-world applications to shift meaningfully [17, 18]. Future implementations could explore strategies such as incorporating mentorship programs, project-based learning, or industry collaborations to strengthen students' sense of engagement and belonging in QC. Furthermore, engagement and usability ratings ($M = 3.90, SD = 0.87$) indicate that students generally found the tool intuitive and engaging. However, technical challenges, including minor software bugs and glitches, were reported by some participants. These usability issues may have moderated the overall learning experience, reinforcing the importance of refining the tool's technical robustness to maximize its impact [44]. Future research should examine the relationship between usability, engagement, and learning outcomes, potentially considering engagement as a mediating factor in the effectiveness of QC learning tools.

The integration of interactive, hardware-supported QC learning tools has significant implications for STEM education and workforce preparation. First, these tools can broaden participation beyond traditional physics and computing disciplines, making QC education more accessible to students with diverse academic backgrounds. Second, this study contributes to ongoing efforts to promote equitable access to advanced technologies, fostering inclusivity in STEM education. Third, the development of scalable and adaptable QC education tools represents a step forward in enhancing the infrastructure for quantum education and workforce development.

While this study provides valuable insights into the role of the MBL and SBL tool in QC education, several limitations should be considered when interpreting the findings. First, the sample size (N = 19) is relatively small, future studies should include a larger and more diverse participant pool to strengthen the robustness of the findings. Second, the study was conducted over a short intervention period (two weeks), which may not fully capture long-term retention and attitudinal shifts. Longitudinal studies examining sustained engagement and learning gains are needed.

Acknowledgements

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