QUANTUM LEARNING: INSIGHTS FROM CASE STUDY IN AI ENGINEERING EDUCATION

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ABSTRACT

This communication examines the integration of quantum computing into AI engineering education, with a specific focus on aligning the course design with CDIO Standards. Authored by the module's instructor and three participating students, it narrates the experience of integrating Quantum Computing into the curriculum and the interdisciplinary knowledge it encompasses. The course curriculum drew from essential scientific domains such as linear algebra, differential and integral calculus, statistics, group theory, quantum mechanics, electromagnetism, information theory, algorithmic thinking, computational complexity, and numerical simulation. These domains are traditionally part of the foundational studies in an undergraduate engineering program and were effectively utilized as building blocks for understanding Quantum Computing. The paper explores the idea of introducing this novel field early in the undergraduate engineering cycle, using it as a cornerstone that ties together various fundamental and specialized fields of knowledge. A survey conducted among the students indicated a strong agreement that the Quantum Computing course fits naturally within the earlier stages of their engineering education, allowing for a practical application of many concepts learned during this period. The paper demonstrates the feasibility and benefits of employing Quantum Computing as a comprehensive educational tool. It argues that such integration aligns with and enhances the core objectives of undergraduate engineering programs, providing a cohesive learning journey from fundamental principles to advanced applications. The student survey results reinforce this proposition, suggesting that such a course could serve as an effective pedagogical strategy to consolidate and apply the broad spectrum of topics covered in the engineering curriculum.

KEYWORDS

Quantum Computing, Pedagogy Engineering Education, Curriculum Development, Interdisciplinary Teaching, CDIO Standards: 2,4,5,7,8,9,11

INTRODUCTION

Quantum computing is an emerging area that combines elements of physics, mathematics, and computer science (Kaswan, 2023). It is considered as a remarkably interesting and challenging area in science and engineering, with many potential uses in different fields (Amin et al., 2019). Indeed, this field provides a wide range of application opportunities, including optimization, machine learning, and simulations of chemical, physical, and biological systems (Pal & al., 2023) and (Hidary, 2019). It contributes significantly to telecommunications and information transmission, advancing medical technologies, and developing new materials to tackle health and environmental challenges (Aithal, 2023). A 2017 Forbes Magazine article by Marr emphasized the transformative impact of quantum computers across various sectors (Marr, 2017). Moreover, this domain has recently witnessed rapid progress, making it one of the fastest-evolving sectors within science, technology, engineering, and mathematics (STEM) (Majumdar, 2023). This advancement is receiving significant financial support from governments, funding agencies, and businesses. They aim to fully utilize the capabilities of quantum computing by making advancements in both the machinery and software aspects.

Quantum Computing (QC) has the potential to play a vital role in secure communication networks through quantum cryptography, enhancing data encryption, and security. It is instrumental in optimizing network design and traffic management, potentially transforming the telecommunications industry (Muruganantham, 2020). In material science, it aids in discovering new materials, and in finance, it assists in complex risk analysis and portfolio optimization (Orús, 2019). The field's multidisciplinary nature makes it an ideal subject for engineering education frameworks that emphasize practical, real-world applications and interdisciplinary learning. Indeed, quantum computing demonstrates the relevance of complex theoretical concepts in tangible applications, resonating with CDIO Standard 3: Integrated Curriculum. This mixing of different areas of knowledge helps gain a deep understanding, which is important for today's engineering problems (Aithal, 2023).

The complexity of quantum computing, demanding both theoretical and practical knowledge, aligns well with CDIO Standard 2: Learning Outcomes (CDIO, 2024). Indeed, it requires a curriculum that cultivates a deep understanding of basic principles while also improving skills in problem-solving, critical thinking, and innovation (Hallenga-Brink, 2017). Thus, quantum computing is not merely a subject of study but an all-encompassing educational approach that integrates smoothly with the CDIO standards and syllabus, especially when considered alongside the various disciplines that form its foundation. The integration of QC into AI engineering education, as narrated in this paper, is an example of how multidisciplinary knowledge can enrich the learning experience, in line with the CDIO standards.

CONTEXT OF QUANTUM COMPUTING IN MODERN EDUCATION

The rising interest in quantum technologies has led to a demand for a well-trained workforce across various sectors. Universities are responding by introducing quantum computing programs and courses at both undergraduate and graduate levels (Hidary, 2019). Moreover, QC has captivated the attention of academia and industry alike (Carberry, 2021). Particularly in AI engineering, where innovation and adaptability are key, the inclusion of QC education provides a holistic view of both theoretical and practical aspects of modern technology (Fernández Pérez, 2022). QC is a melting pot of various fields, each contributing a unique perspective and essential skills. Mathematics, with its branches like linear algebra and calculus, forms the foundation upon which quantum theories are built. Algorithmics and programming bridge the gap between theoretical concepts and practical applications. Quantum mechanics and classical physics provide the necessary scientific background, deepening the understanding of Quantum Computing's operational principles. In addition, complexity theories offer insights into the computational potential and limitations of quantum algorithms (Njeri, 2023). By encapsulating various disciplines, QC education allows teachers to build integrated learning experience (Cheah, 2021) according to the 7th CDIO standard (CDIO, 2024).

This paper is a narrative of a case study of a QC course offered to final-year AI engineering students. Authored by the module's instructor and participating students, it sheds light on the experience and impacts of integrating such a multidimensional subject into the engineering curriculum. Through this study, we aim to demonstrate the feasibility and benefits of employing QC as a comprehensive educational tool, arguing for its inclusion right from the initial stages of undergraduate engineering programs.

CASE STUDY OVERVIEW

Background of the Course

This QC course is planned for final-year-students (5th year in a five years engineering program) in the AI class. We aim to teach them about the basics and uses of quantum computing, especially in machine learning. It covers different scientific areas for a wide understanding of QC. It broadens students' horizons in AI and machine learning advancements by integrating quantum computing into the comprehensive AI engineering curriculum, bridging the gap between fundamental engineering principles and cutting-edge computational technologies.

Interdisciplinary Curriculum Components

The curriculum merged various subjects, each contributing to forming a full understanding of QC:

Mathematics: Topics like linear algebra and calculus were pivotal in understanding quantum algorithms and their theoretical foundations.

Algorithmics: Students explored the development and analysis of quantum algorithms, gaining insights into their computational complexity and efficiency.

Python Programming: Practical sessions using Python, with libraries like Qiskit, allowed students to implement and simulate quantum algorithms, translating theory into practice.

Quantum Mechanics: Fundamental concepts of quantum mechanics were essential for grasping the operational principles of quantum computers.

Classical Physics: A solid grounding in classical physics helped students appreciate the contrast and evolution from classical to quantum computing.

Methodology and Teaching Approach

The course employed a blend of interactive lectures, lab sessions, and project-based learning. Students were encouraged to participate in discussions, work on group projects, and engage in hands-on lab activities, enabling them to apply theoretical knowledge to experimentation on simulators.

Student Engagement and Learning Outcomes

To evaluate the course's impact, a survey featuring open-ended questions was administered to the 36 students who participated. The students' responses were not collected in one shot, but by interview during the 7 weeks duration of the course. The feedback was positive overall, with students highlighting the course's role in solidifying their understanding of previously learned concepts and their relevance. The survey also revealed that students appreciated the interdisciplinary nature of the curriculum, which provided them with a more integrated and cohesive learning experience. The learning outcomes met expectations, with students demonstrating a comprehension of QC principles and their applications in AI engineering.

Course Objectives:

- *Understand the Fundamentals of Quantum Computing*: Grasp the basic principles of quantum mechanics as they apply to computing.
- *Learn Quantum Algorithms:* Explore key quantum algorithms and their implications in computing.
- *Application in Machine Learning:* Understand how quantum computing can revolutionize machine learning.
- *Hands-On Experience:* Gain practical skills through simulations and programming exercises in a quantum computing environment.
- *Future Perspectives:* Discuss the potential and challenges of quantum computing in machine learning.

Intended Learning Outcomes (ILOs):

- *Explain Key Quantum Concepts:* Describe quantum bits, superposition, and entanglement.
- *Demonstrate Understanding of Quantum Algorithms:* Such as Shor's algorithm, Grover's algorithm, and quantum Fourier transform.
- *Apply Quantum Principles in Machine Learning:* Implement basic quantum machine learning algorithms.
- *Develop Quantum Programs:* Use quantum programming languages for simple tasks.
- *Critically Analyze the Impact of Quantum Computing* On future developments in machine learning and AI.

ALIGNMENT OF THE MODULE WITH CDIO STANDARDS 3.0

The relevant CDIO standards (CDIO, 2024) related to the course Quantum Computing, considering its objectives and structure, are as follows:

CDIO Standard 2: Learning Outcomes

This standard is crucial as the course has specific Intended Learning Outcomes (ILOs) that encompass understanding quantum computing concepts, developing quantum programming skills, and applying these in the context of machine learning.

CDIO Standard 3: Integrated Curriculum

The course integrates fundamental knowledge in quantum mechanics with advanced quantum computing and machine learning concepts, providing an interconnected and comprehensive learning experience.

CDIO Standard 5: Design-Implement Experiences

The Quantum Computing (QC) course aligns effectively with CDIO Standard 5, which emphasizes the importance of design-implement experiences in engineering education. This alignment is evident through the course's structure and its integration of practical, hands-on experiences that progressively build in complexity.

CDIO Standard 7: Integrated Learning Experiences

This standard is relevant due to the course’s combination of theoretical knowledge with practical applications, ensuring that students can apply their academic learning in real-world contexts.

CDIO Standard 8: Active Learning

Given the course's interactive format, including quizzes and programming exercises, it aligns with active learning methodologies, encouraging student engagement and deeper understanding.

CDIO Standard 11: Learning Assessment

The diverse assessment methods (quizzes, programming assignment, and final project) in the course are in line with this standard, providing a comprehensive evaluation of the students’ understanding and skills.

The above standards are particularly pertinent due to their emphasis on learning outcomes, integrated and active learning approaches, practical application of knowledge, and comprehensive assessment methods, all of which are key components of the course syllabus.

RELEVANCE OF THE MODULE WITH CDIO SYLLABUS 3.0

The quantum computing (QC) module in AI engineering education aligns seamlessly with the comprehensive framework of the CDIO Syllabus 3.0, addressing multiple aspects of engineering education and professional development.

Fundamental Knowledge and Reasoning

1.1-1.3 Knowledge in Mathematics, Sciences, and Advanced Engineering

The QC module deeply integrates with sections 1.1 to 1.3 of the CDIO syllabus. It encompasses essential mathematics and sciences, notably linear algebra and quantum mechanics, and extends to advanced engineering concepts critical for understanding quantum algorithms and computational complexity. This rigorous academic foundation is vital for developing students' engineering reasoning and problem-solving skills.

Personal and Professional Skills and Attributes

2.1 Engineering Reasoning and Problem Solving

Sections 2.1.1 to 2.1.5 of the CDIO are particularly addressed through the module's focus on problem identification, modeling, and analysis within the complex domain of QC. Students learn to navigate uncertainties inherent in quantum systems, enhancing their analytical skills and ability to formulate classical computing problems in the framework of QC.

2.2 Experimentation and Knowledge Discovery

The module encourages students to engage in experimentation (2.2.3) and hypothesis testing (2.2.4), particularly through lab sessions and Python programming exercises. This hands-on approach develops a deeper understanding of QC concepts and their practical applications.

2.3-2.4 System Thinking and Attributes

The interdisciplinary nature of the QC module cultivates system thinking (2.3.1-2.3.4), encouraging students to view QC within the larger context of engineering systems. It also enhances attributes like creative and critical thinking (2.4.4-2.4.6), preparing students for the complexities of actual engineering challenges.

Interpersonal Skills: Collaboration, Teamwork, and Communication

3.1 Teamwork and Collaboration

The collaborative projects within the module promote teamwork (3.1.1) and multi-perspective collaboration (3.1.2), reflecting the interdisciplinary essence of QC. Engaging with peers from various backgrounds encourages a comprehensive approach to problem-solving.

Conceiving, Designing, Implementing, and Operating Systems

4.1-4.6 The Innovation Process

The QC module directly contributes to students' understanding of the entire innovation process (4.1-4.6), from conceiving and designing quantum algorithms to implementing and operating them. This comprehensive approach aligns with the CDIO's emphasis on practical, real-world engineering experiences.

The Extended CDIO Syllabus: Leadership, Entrepreneurship, and Research

5.1-5.3 Leadership, Entrepreneurship, and Research

Finally, the QC module touches upon leadership (5.1), entrepreneurship (5.2), and research (5.3). Students are encouraged to lead innovative projects, explore entrepreneurial aspects of QC technology, and engage in research, preparing them for leadership roles in the engineering sector.

The above analysis shows that QC module is a robust embodiment of the CDIO Syllabus 3.0, promoting a comprehensive, interdisciplinary, and practical engineering education.

FEEDBACK AND SURVEY FROM STUDENTS ON QUANTUM COMPUTING COURSE

This section collates and analyzes responses gathered from students, offering insights into their experiences and perceptions of the course's structure, content, and impact on their academic and professional outlook.

Summary of Student Feedback

Personal Insights and Expectations

Students entered the course with diverse expectations, ranging from anticipations of hands-on experiences with quantum computers to apprehensions about the course's complexity. As the course progressed, many realized its theoretical focus and the importance of foundational knowledge in quantum computing.

Interdisciplinary Knowledge

A recurring theme in the feedback is the appreciation of the interdisciplinary nature of the course. Students highlighted the integration of concepts from physics, linear algebra, and statistics, which enriched their understanding of quantum computing and demonstrated the practical application of these disciplines.

Early Integration of Quantum Computing Education

Opinions varied on the early introduction of QC in undergraduate education. While some saw it as advantageous for future technological readiness, others expressed concerns about its complexity for early-stage students. The consensus pointed towards its integration in the 2nd to 3rd undergraduate years, aligning with the development of foundational knowledge in relevant scientific domains.

Course Impact on Engineering Curriculum

The QC course was perceived as a significant addition to the engineering curriculum, highlighting a deeper understanding of interdisciplinary connections. It expanded students' perspectives on how different scientific methods can converge in emerging fields like quantum computing.

Long-term Educational Impact

Students acknowledged the potential of quantum computing in reshaping AI and its applications. The course promoted a long-term interest in quantum technologies and their role in future AI advancements.

Analysis of Student Feedback

Themes and Patterns

Common themes include the need for more practical engagement, early integration of QC education, and the course's role in broadening interdisciplinary understanding. Students expressed a desire for a more in-depth exploration of quantum computing concepts and practical applications.

Course Strengths and Areas for Improvement

The course was praised for its comprehensive interdisciplinary approach and theoretical foundation. However, students suggested improvements such as increased hands-on experiences, more in-person teaching, and expanded coverage of advanced topics.

Recommendations for Course Enhancement

1. Enhanced Practical Experience: Incorporate more laboratory sessions or simulations to provide hands-on experience with quantum computing concepts.
2. Interdisciplinary Integration: Continue to strengthen the connection between QC and other scientific domains, through collaborative projects or interdisciplinary workshops.
3. Early Course Introduction: Consider introducing fundamental QC concepts in earlier undergraduate years, aligning with the development of related mathematical and physical knowledge.

The student feedback highlights the QC course's success in developing interdisciplinary understanding and curiosity in quantum computing. However, it also underscores the need for more practical engagement and earlier exposure to QC concepts. These insights are important for refining the course to better meet students' educational needs and interests.

CONCLUSION

The case study from ESPRIT School of Engineering, focusing on the inclusion of quantum computing in the AI engineering curriculum, reveals an educational strategy aligned with the CDIO Standards. The course's design, which integrates quantum computing concepts, reflects a careful consideration of the CDIO Syllabus: It addresses several key areas, including technical knowledge and reasoning, personal and professional skills, and attitudes essential for future engineers. The students' feedback indicates that this methodical approach was effective in enhancing their understanding of the intersection between mathematics, physics, quantum computing and AI. The study also shows the potential benefits of incorporating quantum computing into engineering education early. Indeed, introducing quantum computing early in the curriculum aligns seamlessly with undergraduate studies, as it leverages the math and physics knowledge gained in earlier years. This approach offers an integrated learning experience, enriching the curriculum with practical and theoretical elements that align closely with the CDIO Standards while addressing the CDIO Syllabus.

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