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NSF IUSE: Collaborative Research: Innovating Quantum-Inspired Learning for Undergraduates in Research and Engineering (INQUIRE)

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Abstract

The second quantum revolution has created an urgent national demand for engineers with competencies in quantum information science and technology (QIST). However, QIST curricula remain fragmented, highly theoretical, and poorly aligned with workforce needs, particularly for students without prior preparation in quantum physics. This paper reports on a level-3 NSF IUSE project, Innovating Quantum-Inspired Learning for Undergraduates in Research and Engineering (INQUIRE), now in its third year. The collaborative initiative integrates quantum hardware–software engineering tools, evidence-based instructional design, and competency-based curriculum alignment with the goals of making QIST education accessible. INQUIRE delivers a modular, evidence-based platform that equips engineering educators to introduce QIST concepts effectively, thereby accelerating workforce development and bridging a critical skills gap in quantum technology.

Motivation and Background

Quantum information science and technology has emerged as a strategic national priority in the United States following the passage of the National Quantum Initiative Act [1] and federal investments in QISE education and infrastructure [2]. Quantum computing, communication, and sensing increasingly intersect with semiconductor manufacturing, electronic design automation, and advanced materials research, creating demand for engineers who can bridge quantum theory with practical system design [3].

Despite this demand, undergraduate and early graduate pathways into QIST remain narrow, mathematically intensive, and siloed across disciplines. Early findings from the INQUIRE project indicate that more than three-quarters of students enrolled in introductory quantum computing courses had no prior exposure to quantum-related activities, and over half reported low familiarity with foundational QIS concepts upon entry, underscoring significant access and preparedness barriers for diverse learners [4]. Parallel curriculum analyses at two R1 institutions further revealed that introductory quantum courses emphasize theoretical foundations and software toolchains while offering limited integration of hardware engineering, system-level constraints, or professional competencies aligned with industry expectations [3].

International workforce frameworks highlight this disconnect. The European Competency Framework for Quantum Technologies (ECFQT) defines eight domains and six proficiency levels spanning quantum concepts, hardware and software engineering, applications, and valorization [5,6]. Our early course-mapping studies using ECFQT demonstrate broad conceptual coverage but uneven depth in hardware-centered and professional competency domains [3]. At the same time, engineering education research has shown that multimedia-based learning and simulation-based instruction significantly reduce cognitive load in abstract technical domains and improve conceptual retention and engagement [7,8].

Together, these findings motivate the need for scalable QIST curricula that integrate hardware and software perspectives, align explicitly with workforce competencies, and employ instructional strategies that lower technical and cognitive barriers.

Project Overview

The NSF IUSE: INQUIRE project was launched as a five-year collaborative effort between two R1 institutions to embed experiential QIST modules into mainstream engineering curricula and create a reusable, evidence-based education framework [4].

On the technical front, the project developed a Python-based solver for decomposing large quadratic-unconstrained-binary-optimization (QUBO) problems for execution on quantum-inspired chips and extended it into a multi-user, multi-chip environment hosted on a dedicated Linux server supporting more than ten concurrent users. These tools were integrated into PI-led courses to support hands-on simulations of 16-nm FinFET ring oscillators, coupled-oscillator circuits in SPICE, and behavioral modeling using Verilog [9-11].

Instructionally, INQUIRE modules incorporated multimedia-based lectures, simulation-driven assignments [5, 12, 13], inquiry-based classroom activities [3], and project-based assessments [3] organized around the nine QIS concepts proposed by NSF [14]. Learning outcomes are mapped to ECFQT domains to provide transparency in competency development and to support cross-institutional comparison [6]. In parallel, the project is developing a custom large-language-model-based chatbot grounded in a rigorously defined QIST taxonomy to provide scalable conceptual explanations, debugging support, and metacognitive prompts.

Methods

The INQUIRE team adopted a fully mixed-methods approach, intertwining quantitative measurement with interpretive inquiry to capture the full range of learning, engagement, and faculty experience that arises when deploying a quantum-inspired curriculum.

Undergraduate and graduate cohorts at one of the two R1 institutions were the primary subjects. The longitudinal quantum-hardware course enrolled 30 students over three consecutive semesters (Fall 2022, Spring 2024, Spring 2025). Faculty implementing the modular content were three instructors attached to the dual-home courses, and a convenience sample of three faculty from two additional universities was recruited to evaluate the broader adoption effort.

Students completed pre- and post-course reflections that employed a 5-point Likert scale on confidence, conceptual understanding, and perceived relevance. Additional items captured affective engagement (interest, curiosity) and self-effort expectations. Trained observers coded instructor-learner interactions using the Classroom Observation Protocol for Undergraduate STEM (COPUS) [15].

Six faculty and two students were interviewed. The semi-structured interview probed perceptions of the modular platform, perceived alignment with industry needs, time investment for materials adaptation, and experiences in troubleshooting via the chatbot. Interviews were audio-recorded, transcribed verbatim, and thematically coded with MAXQDA.

Instructional artifacts (lecture slides, problem sets) were coded using ECFQT v2.5 rubric. Each artifact was tagged for domain (hardware, software, physical foundations, professional competencies, etc.) and depth of treatment (introductory, intermediate, advanced). Also, Canvas analytics were used to quantify engagement patterns and triangulated with qualitative analyses of instructional design changes and assessment structure [16].

The University of Florida's Institutional Review Board approved all procedures, and all participants provided informed consent.

Results

According to the pre- post measures, students reported heightened confidence in foundational QIS concepts such as quantum states, qubits, and entanglement. They consistently rated simulation-based assignments and hardware-informed modeling activities as the most beneficial instructional components [3-5].

The longitudinal quantum-hardware course analysis revealed consistently high performance across offerings, alongside declining LMS page views over time, indicative of increasingly streamlined course organization and reduced extraneous cognitive load rather than diminished learning outcomes [16]. ECFQT mapping demonstrated evidence of all eight competency domains each semester, with persistent emphasis on Quantum Hardware, Physical Foundations, and Enabling Technologies, reflecting alignment with workforce preparation.

Qualitative interviews with six faculty revealed a consensus that the content aligned with industry expectations, especially in the hardware and professional competency domains identified by the ECFQT rubric. Faculty noted that tailoring assessment rubrics to local course goals still required an initial 4–6 hour investment. Implementation challenges that emerged from the interviews conducted outside the INQUIRE teams highlighted important considerations for broader adoption. One recurring issue involved faculty preparedness. Instructors without prior experience using quantum-inspired computational tools frequently reported a significant learning curve, particularly when attempting to integrate simulation-based laboratory activities into courses traditionally organized around lecture-centered delivery. The transition required pedagogical adjustment in balancing conceptual instruction with computational experimentation. Although the modular design of the content was intended to support flexibility, aligning these modules with existing course structures often required discipline-specific restructuring of instructional sequences and assessment timing, potentially creating tension with preexisting course content that left limited room for additional material.

Beyond formal coursework, INQUIRE modules has been disseminated internationally through presentations in Canada and South Korea. Middle-school quantum computing mini-workshops hosted during annual university Code-A-Thon events further extended pipeline development by introducing early learners to QIST concepts.

Conclusion

This work demonstrates that the intentional integration of quantum-inspired hardware and software tools with instructional design grounded in learning sciences can enhance the accessibility and educational effectiveness of QIST for students, while simultaneously strengthening alignment with workforce requirements. The INQUIRE project emphasizes the development of instructional materials that are adoptable and adaptable across institutional contexts, the dissemination of open educational resources, and sustained faculty support for curricular integration. Beyond formal coursework, continued engagement with K–12 learners and community partners serve to cultivate early interest in quantum technologies and to expand participation. Future work will include longitudinal analyses of students' academic and career trajectories, further development of AI-enabled instructional scaffolds for large-enrollment courses, and continued incorporation of context-rich, application-oriented quantum modules into core engineering curricula.

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