A Longitudinal Analysis of Competency Development in a Quantum Hardware Course

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Syed Hassan Tanvir is a PhD student at the University of Florida. He has over a decade of experience teaching in various engineering programs and working in interdisciplinary professional engineering environments. His research focuses on the intersection of learning styles, cognitive processes, and competency-based education within engineering curricula. He is currently involved in an NSF-funded project investigating instructional design and competency development in Quantum Information Science and Quantum Hardware courses. With the rapid advancement of large language models (LLMs), his recent work explores the integration of AI-driven tools and LLMs into engineering curricula to enhance conceptual learning, assessment, and student engagement. His broader research interests include curriculum design, assessment of professional competencies, and data-driven approaches to improving learning outcomes in engineering education.

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A Longitudinal Mixed-Methods Analysis of Engagement, Multimedia Pedagogy, and Competency Development in an Upper-level Quantum Hardware Course

Abstract

This study builds on three years of findings from an NSF-funded project aimed at enhancing the curriculum for Quantum Information Science (QIS). The accelerating convergence of semiconductor technology and QIS underscores the growing need for engineers with a strong foundation in QIS fundamentals and the professional competencies for interdisciplinary collaboration. Key QIS concepts, including superposition, entanglement, and quantum measurement, form the conceptual basis for innovation in quantum devices. However, limited empirical research has examined how these abstract principles are taught within engineering curricula, particularly for students with limited exposure to quantum mechanics or quantum physics. To address this gap, this study examines the evolution of an upper-level undergraduate/early graduate-level Quantum Hardware course across three offerings (Fall 2022, Spring 2024, and Spring 2025) to support conceptual understanding and professional skill development at an R1 institution in the United States. Specifically, the study explores the following research questions: (RQ1): How have instructional practices and student engagement changed over time across course offerings, and what patterns are observable in engagement with the quantum hardware course? (RQ2): How are European Competency Framework for Quantum Technologies (ECFQT) v2.5 competencies represented and supported through instructional materials, classroom activities, and assessments, and how do these supports vary across course offerings?

Using a longitudinal, mixed-methods design, the research analyzes course data from one R1 institution. Quantitative engagement analytics (e.g., page views, time on task, submission rates, and discussion participation) are integrated with qualitative analyses of lectures, assignments, and project descriptions. Guided by a constructivist learning framework, the study evaluates how instructional design balances conceptual rigor with applied practice. Findings are interpreted using ECFQT to assess coverage with global competency domains. Results reveal a shift toward project-based, semiconductor-contextualized pedagogy that integrates QIS fundamentals with transferable professional skills. The study provides evidence-based insights to advance quantum engineering education and workforce preparation.

1 Introduction

As the second quantum revolution reshapes research and industry, Quantum Information Science and Technology (QIST) has become a strategic priority globally and a national priority in the United States [1–3]. The U.S. National Quantum Initiative Act and related global efforts underscore the urgent need for a quantum workforce capable of translating quantum concepts into practical engineering capabilities [4–6]. Engineers who can understand, design, and evaluate quantum hardware are especially critical, because advances in superconducting circuits and semiconductor-based platforms are shaping the performance, scalability, and reliability of next-generation quantum technologies. However, despite accelerating demand, universities continue to face persistent challenges in preparing students, particularly engineering students, to engage meaningfully with quantum hardware concepts and practices [7]. One contributing factor is that while quantum mechanics is typically a core requirement for physics majors, exposure to quantum content in many other STEM pathways is often elective or dependent on student choice, leaving incoming students with highly uneven preparation. Consequently, many students enter upper-level undergraduate/early graduate-level QIST courses with limited prior exposure to quantum mechanics, making it difficult to build accurate mental models and connect foundational concepts to hardware implementations [8]. These bottlenecks are amplified in quantum

hardware courses, which require students to integrate quantum physics, materials science, electrical engineering, and computation [7]. As a result, designing instruction that supports conceptual understanding, reduces cognitive load, and builds relevant professional competencies has become a priority for QIST educators. At the same time, empirical evidence on how upper-level undergraduate/early graduate quantum hardware courses evolve over time in R1 institutions remains limited. We focus on R1 settings because instruction is often closely tied to fast-moving research, specialized infrastructure. Accordingly, understanding how instruction naturally evolves across offerings in an R1 context can illuminate how both engagement and competency-building opportunities shift over time.
This study analyzes three offerings of an upper-level undergraduate/early graduate-level Quantum Hardware course at a U.S. R1 institution (Fall 2022, Spring 2024, Spring 2025). Across offerings, instruction shifted from text-heavy lectures to more visually enriched materials and, most recently, to a multimedia-supported design incorporating conceptual animations and simulation-based interactive explanations. Notably, these changes were not guided by a formal competency framework; rather, they reflect the instructor's iterative pedagogical refinements, creating a natural context to examine how competency-building opportunities emerge as course materials evolve. To characterize these emergent competencies, we adopt the European Competence Framework for Quantum Technologies (ECFQT v2.5) as an analytical lens [6]. ECFQT v2.5 specifies workforce-relevant knowledge and skills across eight domains and forty-two subdomains. Using ECFQT for analysis, rather than as a design blueprint, enables us to assess how the course's instructional artifacts and assessments align with global expectations for quantum workforce preparation. Specifically, this study addressed the following two research questions: (RQ1): How have instructional practices and student engagement changed over time across course offerings, and what patterns are observable in engagement with the quantum hardware course? (RQ2) How are ECFQT v2.5 competencies represented and supported through instructional materials, classroom activities, and assessments, and how do these supports vary across course offerings? Together, these research questions provide a longitudinal account of how instructional evolution relates to student engagement and the emergence of ECFQT-aligned competency-building opportunities in an upper-level undergraduate/early graduate-level quantum hardware course.

2 Literature Review

Quantum Information Science (QIS) concepts are inherently abstract and frequently counterintuitive, and learners may therefore develop incomplete or non-productive mental models that impede later learning and transfer [9]. Consistent with this, prior research shows that students commonly struggle with QIS foundational concepts such as superposition, measurement, entanglement, coherence, and decoherence [10, 11]. These difficulties can be amplified for non-physics majors, particularly electrical engineering students, who may enter early graduate QIST coursework with uneven preparation in quantum mechanics and quantum physics [7, 8]. As a result, they must simultaneously integrate quantum physics with electronics, materials science, and signal processing, often within a single course context. This interdisciplinary integration increases intrinsic cognitive load [7] and may hinder conceptual understanding, especially in quantum hardware courses where superconducting, trapped-ion, photonic, or semiconductor-based qubits must be interpreted through both physical principles and engineering constraints. Therefore, it is important to examine not only what is taught in an upper-level undergraduate/early graduate-level quantum hardware courses, but also how instruction evolves across offerings and what kinds of learning opportunities such evolution creates. Because quantum hardware courses require students to connect abstract quantum principles with engineering constraints, examining instructional evolution across offerings helps reveal how course design supports scaffolding, application-oriented learning, and competency development beyond content coverage. Empirical studies of when upper-level undergraduate/early graduate-level quantum hardware courses evolve across multiple offerings in R1 institutions remain limited. This gap matters because, in R1 settings, instructional refinements often track fast-moving research and specialized infrastructure, and can shape not only conceptual understanding but also workforce-relevant competencies.

Student engagement is commonly understood as a multidimensional construct that includes behavioral, emotional, and cognitive dimensions [12]. In this study, we focus specifically on behavioral engagement because the available longitudinal data capture observable student actions within the learning management system rather than students' internal motivation, affect, or cognitive processing. LMS-visible indicators such as page views, participation counts, and on-time assignment submission patterns provide useful insights into how students access course materials, engage with course activities, and complete required tasks across offerings. Although these indicators do not fully represent learning or conceptual engagement, they can provide meaningful evidence of participation patterns when interpreted alongside instructional context and artifact-based analysis. Therefore, examining behavioral engagement alongside instructional materials enables this study to examine how course redesign and multimedia-supported pedagogy may have shaped students' observable engagement over time.

To examine course evolution through this broader lens, we adopt the European Competence Framework for Quantum Technologies (ECFQT) a periodically updated competency framework spanning Version 1.0 [13], Version 2.0 [14], Version 2.5 [15], and the latest Version 3.0 [16] that evolves to reflect technological advances, emerging workforce competency needs, and pedagogical best practices. For this longitudinal study, we use ECFQT v2.5 as a stable analytical baseline because it was the established reference at the start of our dataset (Fall 2022) and provides the domain/subdomain taxonomy and proficiency scale needed for consistent cross-offering comparison; we acknowledge that v3.0 (April 2025) introduces clarifications and is accompanied by an added QT proficiency certification scheme, but adopting it midstream would reduce comparability across earlier offerings. ECFQT further defines six ascending proficiency levels (A1–C2), which enable consistent interpretation of learning depth from introductory awareness and literacy (A1–A2) to utilisation and investigation (B1–B2) and advanced specialisation and innovation (C1–C2); consistent with our prior work that also applied ECFQT v2.5 and operationalized these proficiency descriptors, we summarize the A1–C2 levels across the framework's proficiency triangle our previous work in Table 1 [17]. Using ECFQT as an analytical lens (rather than a design blueprint) allows us to interpret course evolution not only in terms of content coverage but also in terms of the competency-building opportunities embedded in instructional materials and assessments.

3 Theoretical and Analytical Framework

This study is informed by constructivist learning theory [18], which emphasizes active knowledge construction through authentic problem-solving and contextualized application. The Cognitive Theory of Multimedia Learning (CTML) [19], and behavioral models of student engagement [12]. These perspectives frame how instructional evolution relates to observable engagement patterns and competency development. In a quantum hardware course where abstract principles must be reconciled with engineering constraints, shifts toward project-centered, application-oriented instruction reflect a move beyond the transmission of formal derivations toward knowledge construction. CTML posits that coordinated visual and verbal representations enhance learning by reducing extraneous cognitive load and supporting meaningful processing [19]. The transition from text-dense to multimedia-supported materials is therefore interpreted as improving instructional coherence, signaling, and schema formation. In this study, engagement is operationalized as observable behavioral participation within the LMS environment, including page views, participation counts, and on-time submission rates.

4 Methods

This study employed a longitudinal convergent parallel mixed-methods design [20] to examine the evolution of an upper-level undergraduate/early graduate-level Quantum Hardware course across three offerings: Fall 2022, Spring 2024, and Spring 2025. The study focused on the relationships among instructional changes, student engagement, and competency development by integrating quantitative Canvas learning analytics with qualitative ECFQT-guided analysis of instructional artifacts.

The study was conducted in a 3-credit-hour, in-person Quantum Hardware course at the University of Florida. The course primarily enrolled graduate students in electrical and computer engineering and related STEM fields, with some upper-level undergraduate students. The course was delivered over a 16-week semester and required foundational preparation in solid-state physics, while prior exposure to quantum mechanics was recommended. As a result, incoming cohorts exhibited variation in quantum preparation, particularly among students from different STEM pathways. Consistent with prior work [8], instructional materials evolved from text-dense, derivation-centered slides in 2022 toward visually scaffolded materials in 2024, curated primary research literature, and multimedia-supported instruction in 2025, including annotated diagrams and simulations.

The study integrated two complementary data sources: (1) instructional artifacts, including weekly lecture slide decks, homework sets, readings, and project guidelines, and (2) Canvas learning analytics, including page views, participation indicators, grades, and on-time assignment submission patterns. In this study, student engagement was conceptualized as behavioral engagement and operationalized through LMS-visible indicators, including Canvas page views, participation counts, and on-time assignment submission patterns. These indicators captured students' observable interactions with course resources and course tasks in Canvas, rather than cognitive or emotional engagement. Course grades were used as a performance indicator to contextualize engagement patterns across offerings, rather than as a direct measure of engagement. The quantitative strand examined LMS-visible behavioral engagement patterns across offerings, while the qualitative strand used ECFQT-guided coding to examine domain, subdomain, and proficiency-level representation in course materials and assessments. The artifact and analytics strands were analyzed within each offering and then merged through offering-level comparison and triangulation to support an integrated interpretation of engagement patterns (RQ1) and competency representation in course materials and assessments (RQ2).

4.1 Study Population

Across the three offerings analyzed in this study, cohort sizes were modest (Fall 2022: $n = 8$; Spring 2024: $n = 9$; Spring 2025: $n = 13$), which is typical for specialized, upper-level undergraduate/early graduate-level courses. Figure 1 summarizes the study population by academic level across the three offerings. In Fall 2022, enrollment comprised 1 PhD, 5 MS, and 2 undergraduate students ($n = 8$). In Spring 2024, the cohort included 3 PhD, 4 MS, and 2 undergraduate students ($n = 9$). In Spring 2025, the population shifted toward greater doctoral participation, with 6 PhD, 2 MS, and 5 undergraduate students ($n = 13$). Overall, the course attracted a modest but evolving mix of graduate and undergraduate students, with increasing PhD representation in the most recent offering.

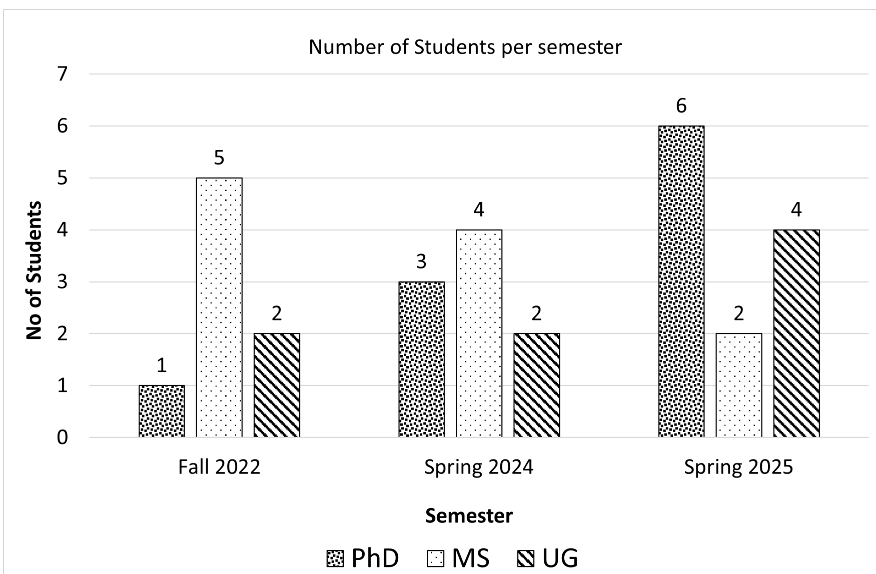

Figure 1: Number of Students per Semester

4.2 Instructional artifacts and ECFQT Coding

Instructional artifacts included weekly lecture slide decks (16 weeks per offering) and aligned materials (readings, homework, and project guidelines). All artifacts were imported into MAXQDA, a qualitative data analysis software. Using ECFQT v2.5 as an analytical lens, we mapped course content to the framework's eight domains and forty-two subdomains to characterize the breadth and depth of competency-building opportunities represented in the instructional materials. The ECFQT domain–subdomain structure served as the primary codebook, enabling consistent, topic-wise categorization of lecture content and aligned artifacts across offerings and supporting comparative analysis of how competency coverage shifted over time. Table 1 provides an illustrative excerpt of the ECFQT codebook and scoring rubric used in this study, including the 0–3 instructional emphasis rubric (0 = not evident; 1 = introduced; 2 = covered; 3 = emphasized) and the dominant A1–B2 proficiency classification based on the primary cognitive demand reflected in slides, homework prompts, and project deliverables. For example, when superposition appeared in a lecture slide or homework problem, the segment was coded under ECFQT Domain 1, Concepts and Foundations, subdomain 1.1 Basic quantum concepts. A brief definition of superposition as a linear combination of basis states was coded as "introduced" with an A2-level proficiency because it required conceptual explanation. When students were asked to calculate measurement probabilities from a given qubit state, the same topic was coded as B1 because the task required applying the concept in a routine quantitative problem. If superposition was revisited across multiple slides, homework tasks, or simulations, the instructional intensity was increased to "emphasized" based on repeated and assessed use of the concept.

To support coding consistency, two coders independently completed an initial coding cycle of the instructional artifacts ($n = 1966$ pages) to identify where course content aligned with the ECFQT domain codes (D1–D8). Both coders also wrote analytic memos to document first impressions, questions, and emerging decision rules. Outputs from this first cycle were used to refine the codebook by clarifying domain definitions and specifying evidence anchors for assigning domain labels to artifact segments. In a second coding cycle, both coders applied the finalized ECFQT domain codebook and compared their domain assignments for the same segments to evaluate interrater consistency. Agreement was assessed using Cohen's kappa ($\kappa = 0.80$), indicating strong consistency, and all discrepancies were discussed and resolved before finalizing the coded dataset. Cohen's kappa was computed for ECFQT domain assignment (D1–D8); intensity and proficiency ratings were reconciled through discussion using the evidence anchors in Table 1.

Table 1: ECFQT v2.5 Codebook Excerpt and Scoring Anchors (Illustrative Rows)

ECFQT Domain	**ECFQT subdomain (code)**	**Intensity evidence (0-3)**	**Proficiency evidence (A1–B2)**
Domain 1: Concepts & Foundations	(1.1) Basic quantum concepts	Definition + use across slides/assessments	Explain concept; apply to interpret outcomes or solve problems
Domain 2: Physical Foundations of QT	(2.3) Solid State Physics	Formalism introduced + used in tasks	Explain representations; compute/apply operators; analyze measurement results
Domain 4:Quantum Hardware	(4.1) Superconducting circuits	Hardware models/diagrams + assessed tasks	Explain architecture; apply models; analyze parameters/trade-offs
Domain 8 Valorisation	(8.1) Industry landscape	Industry context required in deliverables	Describe landscape; compare options; justify choices under constraints

Note. **Intensity (0–3)**: **0** not evident; **1** introduced (brief mention/definition); **2** covered (explained with example or problem); **3** emphasized (repeated across weeks and/or assessed). **Proficiency (A1–B2)**: **A1** Awareness; **A2** Literacy; **B1** Utilization: application in routine problems/standard calculations; **B2** Investigation (analysis/evaluation of less-routine tasks using evidence and constraints).

4.3 Canvas learning analytics

Canvas learning analytics were used to quantify Learning Management System (LMS)-visible engagement across offerings using student-level overall course grade, page views, participation, and on-time assignment submission percentage. Analytics were obtained from de-identified institutional data, with all direct student identifiers removed prior to analysis. Given the modest cohort sizes, our analyses emphasize within-course patterns and triangulation across multiple data sources rather than population-level generalization. In engineering education research, small-n course-based studies are methodologically appropriate when the goal is to generate context-rich, practice-relevant insights through systematic analysis and triangulation rather than population-level inference [21, 22].

5 Results

5.1 Descriptive Trends in Performance and Engagement

Across offerings, grades were uniformly high (including a ceiling effect in Spring 2025), whereas engagement indicators varied across time, as shown in Table 2.

Table 2: Descriptive Statistics for Performance and Engagement by Course Offering

Offering	n	**Grade /100** M **(SD)**	**Page Views** M **(SD)**	**Participations** M **(SD)**
Fall 2022	8	98.92 (1.27)	581.62 (353.22)	25.75 (12.91)
Spring 2024	9	98.63 (2.75)	541.78 (318.18)	10.78 (3.93)
Spring 2025	13	100.00 (0.00)	354.54 (173.17)	5.54 (2.40)

Note. Small-n denotes the sample size by course offering.

Two patterns were salient: participation decreased across offerings, and page views declined by Spring 2025. Since page views largely capture Canvas navigation rather than learning itself, fewer views can reflect more efficient access to materials, offline use (e.g., downloads), or activity occurring outside Canvas. A possible explanation is that the course became easier to follow and navigate over time, reducing cognitive load. In Fall 2022, slides were more text-heavy, likely prompting students to revisit the materials more often, leading to higher page views. In Spring 2024, the instructor redesigned the lectures to focus more on multimedia-based learning techniques [19] and reorganized the Canvas modules, likely reducing the need to search through pages. By Spring 2025, modules were even more streamlined, with topic-aligned links to recent research, further reducing Canvas navigation and shifting some engagement to external resources or offline review, consistent with lower page views and Canvas-recorded participation.

Within-term Spearman correlations, as indicated in Table 3, depict relationships among LMS-visible engagement indicators varied by offering. In Fall 2022, assignment on-time submission percentage was strongly positively associated with participation ($\rho = .758$, $p = .029$). In Spring 2024, page views and participations were strongly positively associated ($\rho = .886$, $p = .0015$). In Spring 2025, grade correlations were not estimable due to a ceiling effect (all grades = 100), and engagement correlations were positive but not statistically significant (e.g., page views–participations: $\rho = .518$, $p = .070$). When pooling data across offerings and controlling for offering, the association between page views and participations remained statistically significant (partial $\rho = .604$, $p = .00041$), whereas associations involving grade were not significant, consistent with restricted grade variability.

Table 4: Longitudinal Coverage of ECFQT Domains and Subdomains Across Course Offerings (Re-evaluated from Mapping File)

Metric	**Fall 2022**	**Spring 2024**	**Spring 2025**
ECFQT domains evidenced (of 8)	8	8	8
Subdomains evidenced (proficiency > 0; of 42)	40	39	32
Subdomains at A2-level (value = 2)	31	31	25
Subdomains at B1-level (value = 3)	8	7	7
Subdomains at B2-level (value = 4)	1	1	0
Subdomains not evident (value = 0)	2	3	10
Primary domains emphasized (highest domain totals)	D4, D5, D2	D4, D2, D5	D4, D3, D2

Note. Domain emphasis is based on the highest aggregated domain totals from the "Intensity 8x3". Proficiency values are encoded as 0 = not evident, 2 = A2, 3 = B1, and 4 = B2 .

Table 3: Spearman correlation among course grade and LMS-visible engagement indicators by offering, and pooled partial correlations controlling for offering.

Offering / Model	Pairwise association	ρ	p	Interpretation
Fall 2022 (n = 8)				
	On-time % ↔ Participations	0.758	.029	Strong positive
	Page Views ↔ Participations	0.301	.468	Small / ns
	Page Views ↔ On-time %	0.295	.479	Small / ns
Spring 2024 (n = 9)				
	Page Views ↔ Participations	0.886	.0015	Very strong positive
	Participations ↔ On-time %	-0.201	.604	Small / ns
	Page Views ↔ On-time %	-0.017	.965	Near zero / ns
Spring 2025 (n = 13)				
	Page Views ↔ Participations	0.518	.070	Moderate positive / ns
	Participations ↔ On-time %	0.479	.098	Moderate positive / ns
	Page Views ↔ On-time %	0.284	.347	Small / ns
Pooled partial Spearman (N = 30; controlling for offering)				
	Page Views ↔ Participations	0.604	.00041	Moderate–strong positive
	Participations ↔ On-time %	0.353	.056	Moderate / marginal
	Page Views ↔ On-time %	0.159	.400	Small / ns
	Grade ↔ Page Views	-0.034	.860	Near zero / ns
	Grade ↔ Participations	0.127	.505	Small / ns

Note. ρ values are Spearman rank-order correlations. "On-time %" denotes assignment on-time submission percentage.

"ns" indicates not statistically significant at $\alpha = .05$. Grade correlations for Spring 2025 are not estimable because grades exhibited zero variance (all students earned 100). Pooled partial correlations were computed after controlling for offering (semesters), to reduce confounding by between-offering differences in LMS activity patterns.

5.2 ECFQT Domain-Level coverage

Mapping evidence was observed for all eight ECFQT domains in each offering (8/8 in Fall 2022, Spring 2024, and Spring 2025), indicating broad domain-level coverage across semesters as shown in Table 4. However, the distribution of emphasis varied across semesters. In Fall 2022, the strongest domain totals were observed in D4 (Quantum Hardware), followed by D5 (Quantum Computing and Simulation) and D2 (Physical Foundations of Quantum Technologies). Spring 2024 showed a similar pattern, with D4 remaining most emphasized and D2 and D5 also prominent. In Spring 2025, D4 remained the most emphasized domain, while the next-highest domains shifted to D3 (Enabling Technologies and Techniques) and D2, suggesting increased relative attention to enabling techniques alongside persistent hardware-centered coverage, as shown in Figure 2.

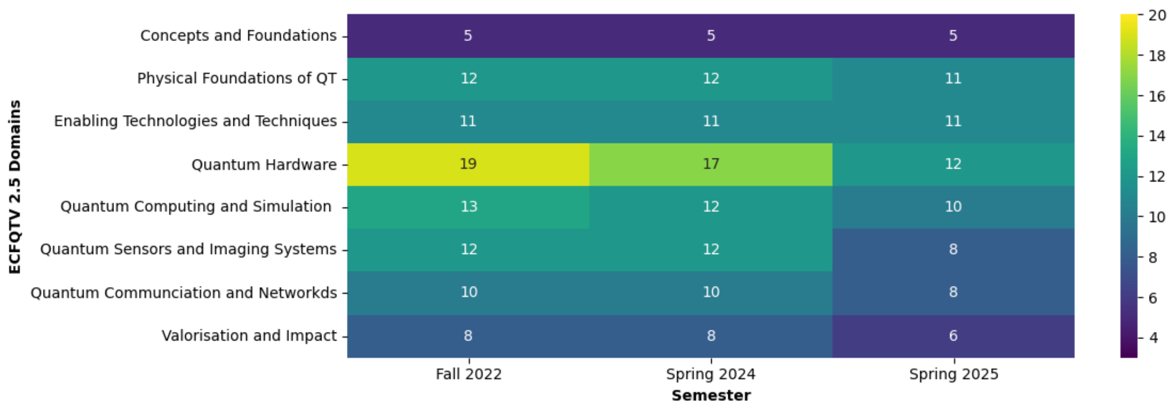

Figure 2: ECFQT Eight Domains Heatmap Over Three-Year offerings

5.3 ECFQT Subdomain Breadth and Proficiency Distribution

Although domain-level coverage remained broad, subdomain-level breadth and depth signals varied across offerings as shown in Table 4. The number of subdomains evidenced (dominant proficiency > 0) was 40/42 in Fall 2022, 39/42 in Spring 2024, and 32/42 in Spring 2025. This indicates that Spring 2025 coverage was distributed across fewer subdomains. Rather than implying diminished instructional quality, this pattern suggests a more concentrated emphasis on a narrower set of competencies, consistent with Spring 2025 focusing more strongly on selected quantum hardware–relevant topics.

Table 5 reports the highest ECFQT proficiency level evidenced in the instructional materials for each domain across Fall 2022, Spring 2024, and Spring 2025. Across all three offerings, the course consistently reached B1 in Domain 1 (Concepts and Foundations), Domain 3 (Enabling Technologies and Techniques), and Domain 4 (Quantum Hardware), indicating stable application-oriented learning opportunities in core, hardware-centered areas. In contrast,Domain 6 (Quantum Sensors and Imaging Systems), Domain 7 (Quantum Communication and Networks), and Domain 8 (Valorisation) remained at A2 in every offering, suggesting these domains were addressed primarily at a conceptual awareness/explanation level.

Two domains showed longitudinal changes in depth. Domain 2 (Physical Foundations of Quantum Technologies) decreased from B2 in Fall 2022 and Spring 2024 to B1 in Spring 2025, and Domain 5 (Quantum Computing and Simulation) decreased from B1 in Fall 2022 to A2 in Spring 2024 and Spring 2025. Overall, the domain-level proficiency profile remains concentrated in the A2-B1 range across offerings, with B2-level evidence appearing only in the earlier semesters and reduced domain-level depth signals in Spring 2025.

Table 5: Highest ECFQT Domain-Level Proficiency Evidenced in Instructional Materials by Semester

Domain	**Fall 2022**	**Spring 2024**	**Spring 2025**
Domain 1: Concepts and Foundations	B1	B1	B1
Domain 2: Physical Foundations of Quantum Technologies	B2	B2	B1
Domain 3: Enabling Technologies and Techniques	B1	B1	B1
Domain 4: Quantum Hardware	B1	B1	B1
Domain 5: Quantum Computing and Simulation	B1	A2	A2
Domain 6: Quantum Sensors and Imaging Systems	A2	A2	A2
Domain 7: Quantum Communication and Networks	A2	A2	A2
Domain 8: Valorisation	A2	A2	A2

Note. Entries indicate the highest proficiency level evidenced in instructional materials for each domain within a semester. A2 = conceptual awareness/explanation; B1–B2 = application, modeling, and/or quantitative analysis.

6 Discussion

Across three offerings, course performance remained uniformly high, with Spring 2025 exhibiting a clear ceiling effect (all students earned 100). This restricted variability likely weakened any observable relationships between grades and LMS-visible engagement, indicating that grades were not sensitive to engagement differences in this context. In contrast, LMS engagement indicators changed meaningfully over time: both page views and participation declined across offerings (Table 2). Because page views largely reflect Canvas navigation rather than learning, lower counts should not be interpreted as reduced engagement. Instead, the pattern is consistent with increasingly efficient access to course resources as the course organization and instructional materials became more streamlined. Improved structure and signaling can reduce extraneous cognitive load and reduce the need for repeated navigation, offering a plausible explanation for lower page views and participation without implying diminished learning activity.

Correlational patterns further suggest that the meaning of LMS-visible engagement varied by semester, as shown in Table 3. In Fall 2022, on-time submission was strongly associated with participation, indicating that students who engaged more in LMS-recorded interactions also tended to submit work on time. In Spring 2024, page views and participation were very strongly aligned, reflecting a coherent pattern of LMS-based engagement. In Spring 2025, engagement correlations remained positive but were not statistically significant, consistent with limited power and the possibility that learning activity increasingly occurred outside Canvas (e.g., Class discussions, activities, offline reviews, or external resources). Notably, after pooling data and controlling for offering, page views, and participation remained significantly related (partial $\rho = .604$), suggesting a stable underlying linkage between these two LMS-visible behaviors despite declining overall levels.

RQ2 results further indicate that the R1 institution's priorities are reflected in the course's competency profile and its evolution. Domain-level mapping evidenced all eight ECFQT domains in each semester (8/8; Table 4), demonstrating near-comprehensive coverage of workforce-relevant competencies. At the same time, the pattern of emphasis is clearly aligned with an electrical engineering–oriented quantum hardware course: Quantum Hardware (D4) remained the most emphasized domain across all offerings as shown in Figure 2, with supporting emphasis concentrated in domains that directly underpin hardware practice, including Physical Foundations (D2) and, in the most recent offering, Enabling Technologies and Techniques (D3) as reflected in Table 4. This shift toward D3 in Spring 2025 is consistent with an R1 emphasis on keeping instruction current—foregrounding enabling techniques and tool-relevant competencies that reflect contemporary research and development practices in quantum engineering.

At the subdomain level, breadth narrowed across offerings (40/42 in Fall 2022; 39/42 in Spring 2024; 32/42 in Spring 2025; Table 4), suggesting a more concentrated competency focus in Spring 2025 rather than reduced quality. This concentration can be interpreted as strategic prioritization—allocating instructional time and assessment emphasis toward the competencies most central to the course's electrical engineering and hardware mission, while still maintaining complete domain-level coverage. The domain-level proficiency summary corroborates this interpretation as depicted in Table 5. B1-level evidence was stable across Concepts and Foundations (D1), Enabling Technologies and Techniques (D3), and Quantum Hardware (D4), indicating consistent, application-oriented opportunities in core domains aligned with hardware-focused engineering practice. In contrast, Sensors/Imaging (D6), Communication/Networks (D7), and Valorisation (D8) remained at A2 across semesters, implying primarily conceptual coverage—an expected pattern for a course whose primary scope is hardware development rather than specialization in sensing, networking, or commercialization. Two domains showed reduced evidence depth over time: Physical Foundations (D2) decreased from B2 to B1 in Spring 2025, and Quantum Computing and Simulation (D5) decreased from B1 (Fall 2022) to A2 (Spring 2024; Spring 2025). Taken together, these shifts suggest that the course sustained broad ECFQT-aligned exposure while increasingly aligning depth and emphasis with the R1 institution's hardware-centered priorities and the incorporation of up-to-date, research-relevant enabling techniques.

7 Limitations

This study has three key limitations. First, cohort sizes were small. (n = 8–13), which limits statistical power and generalizability beyond this course. Second, Spring 2025 grades showed a ceiling effect (all 100), preventing grade-based correlations and making grades less useful for distinguishing performance across offerings. Third, LMS indicators (page views, participations) are proxy measures that capture platform-recorded behavior, not cognitive engagement, offline study, or learning activity outside Canvas.

8 Conclusion and Future Work

This study provides a longitudinal account of how an R1 quantum hardware course maintained consistently high performance while LMS-visible engagement declined across offerings, including a Spring 2025 grade ceiling effect. Rather than indicating reduced learning, declining page views and participations most plausibly reflect more efficient access to materials as the course became more streamlined and better organized, alongside a shift of some learning activity beyond Canvas (e.g., in-class activities, offline review, and external resources). ECFQT mapping further showed broad, workforce-relevant competency-building opportunities across all offerings, with all eight domains evidenced each semester and a persistent electrical engineering, hardware-centered emphasis. Consistent with an R1 research-intensive vision, the course appears to balance comprehensive exposure to the ECFQT competency landscape with deeper, application-oriented support in core hardware-facing domains, while treating adjacent areas (e.g., sensors/imaging, communication/networks, and valorization) primarily at a conceptual level. Overall, the findings suggest that, although the course was not designed using the ECFQT framework, it nevertheless maps closely onto globally articulated quantum workforce competencies: across offerings, iterative instructional refinement preserved strong outcomes while maintaining up-to-date, research- and technique-relevant content and concentrating application-oriented depth in the core hardware-facing domains most central to quantum engineering practice.

Building on these results, future work will leverage additional collected data to triangulate engagement beyond LMS counts, link ECFQT proficiency evidence directly to assessment tasks, and incorporate qualitative context to explain observed shifts across offerings.

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