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Introductory quantum information science coursework at US institutions: content coverage

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Abstract

Despite rapid growth of quantum information science (QIS) workforce development initiatives, perceived lack of agreement among faculty on core content has made prior research-based curriculum and assessment development initiatives difficult to scale. To identify areas of consensus on content coverage, we report findings from a survey of N=63 instructors teaching introductory QIS courses at US institutions of higher learning. We identify a subset of content items common across a large fraction ($\geq$ 80%) of introductory QIS courses that are potentially amenable to research-based curriculum development, with an emphasis on foundational skills in mathematics, physics, and engineering. As a further guide for curriculum development, we also examine differences in content coverage by level (undergraduate/graduate) and discipline. Finally, we briefly discuss the implications of our findings for the development of a research-based QIS assessment at the postsecondary level.

Keywords: Quantum education; Curriculum; Assessment; Quantum information science

1 Introduction and motivation

The long-theorized Second Quantum Revolution [1] is upon us, and educational initiatives in quantum information science (QIS) are growing rapidly at U.S. institutions and worldwide [2–5]. A major driver for this growth has been the U.S. National Quantum Initiative Act of 2018 [6, 7] and similar initiatives worldwide (e.g. [8–10]). Quantum researchers and policymakers alike have expressed the need for educational programs to promote a quantum-ready workforce [11–15] and quantum-literate society [16]. Experts have accordingly called for education researchers to be involved in curriculum design from the start [17, 18].

Yet a key challenge limiting involvement of discipline-based education research (DBER) in the development of research-based QIS curricular materials has been a perceived lack of consensus on the goals of QIS education, much less core content coverage. In our own prior work, faculty have expressed disagreement on foundational issues ranging from the utility of programming activities to the merits of covering famous quantum algorithms [19, 20]. Student backgrounds themselves likewise vary within and across courses [19].

Finding points of similarity across courses is thus especially important if DBER researchers are to be involved in QIS education at scale.

Existing work provides a high-level framework to begin identifying these similarities. As early as the 2000s, educators began to theorize that—much as a successful computer scientist can go an entire career paying minimal heed to the chemistry of silicon or the low-level circuitry of individual 0 s and 1 s—relatively little quantum mechanics is needed to teach students quantum computing, as long as the emphasis is restricted to understanding and programming a quantum computer (as opposed to constructing one) [21–23]. Seegerer *et al.* [24] used interviews with QIS experts to conceptualize the breadth of QIS education, identifying key themes such as superposition, entanglement, quantum gates, quantum circuits, and quantum algorithms that they expected to be shared across courses. We aim to create a complementary roadmap at the granularity of discrete skills and concepts that can readily be translated into curricular materials, assessment items, or other tangible DBER outputs. In other words, we seek to identify the subset of foundational core content (e.g. individual gates, algorithms, or mathematical concepts) sufficiently universal that DBER interventions will not remain confined to any one institution. For more precise targeting, we also examine how this material varies across types of courses.

A focus-group study of experts by Seegerer *et al.* [24] identified five core ideas in quantum computing education: superposition, entanglement, quantum computers, quantum algorithms, and quantum cryptography. Two other studies have used comparable methodologies to come to similar conclusions [25, 26]; of course, each study's respective lists of specific ideas and competencies varies in terms of length and granularity, and the latter two studies extend beyond quantum computing. Our study provides a complementary perspective to this growing body of literature, asking what material is actually covered in real courses (as opposed to expert opinions of what ought to be included).

We emphasize that the purpose of this paper is to explore specifically what is typically taught in a *first course* in QIS theory, not to investigate laboratories or more advanced coursework where content coverage will presumably differ even more significantly. Similarly, we take no stance on what *ought* to be covered in QIS coursework; we believe the question of "ought," though undoubtedly important, is better left to the QIS community as a whole to reflect upon in light of our findings.

1.1 Research questions

Three of our research questions specifically pertain to curriculum development:

- **RQ #1**: Which QIS topics are sufficiently universal across courses to be strong candidates for research-based curriculum development?
- **RQ #2**: Which topics, if any, are more likely to be covered at the undergraduate vs. graduate levels? In other words, are certain topics' inclusion or non-inclusion the hallmark of a graduate or undergraduate QIS course?
- **RQ #3**: How does content coverage of introductory QIS courses vary across the academic discipline in which the course is offered? In other words, are there specific topics whose inclusion or non-inclusion is strongly associated with a specific discipline?

A second motivation for this work (**RQ #4**) was to identify a subset of content instructors deem appropriate for inclusion in a research-based QIS assessment—a stricter criterion than simply whether material is covered in a course:

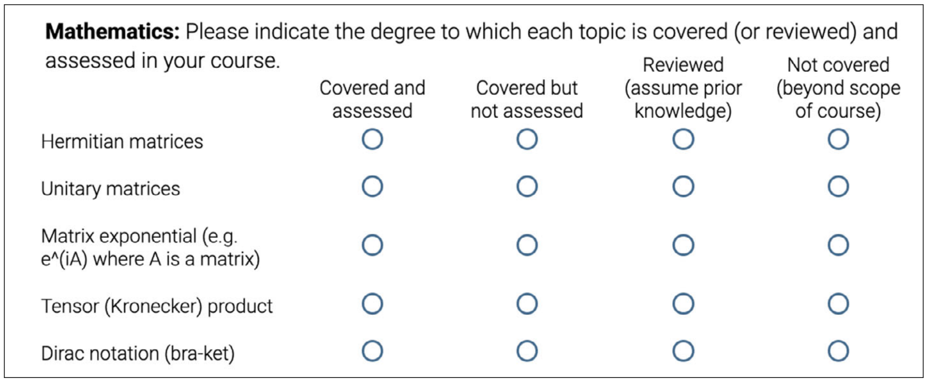


Figure 1 A representative survey question. Screenshot shows top 5 items of a question on mathematical content. Faculty were asked to classify each content item by the degree of content coverage in their course

- **RQ #4**: What subset of QIS topics is suitable for developing a research-based QIS assessment?

Those readers specifically interested in assessment should refer to Sect. 3.4. The remainder of the paper is written for QIS educators and education researchers more broadly.

2 Methodology

2.1 Survey design

Informed by our group's previous experience designing and distributing faculty surveys to inform curriculum development and assessment efforts [19, 27], we developed a survey instrument enabling faculty to classify specific QIS topics by the degree of content coverage in the course. The survey was distributed electronically via Qualtrics.

We first compiled a list of QIS topics drawn from instructor responses to a prior open-ended survey [19], contributed syllabi, and the two QIS textbooks (Refs. [28, 29]) that faculty reported were most frequently assigned in our prior study [19]. Topics were revised, and a few added, based on feedback from QIS educators on our team.[1] The list of topics was converted to survey questions in the manner of Fig. 1. We also collected course background data (e.g. catalog listing) and optional respondent and institution demographics.

Given the dual purposes of our study, we wished to distinguish between content coverage for curriculum development purposes and the stricter threshold of assessability. Accordingly, faculty were allowed to select 1 of 4 options for each content item: "covered and assessed," "covered but not assessed," "reviewed (assume prior knowledge)," and "not covered (beyond scope of course)." The survey instructions included the following definitions:

- **"Covered and assessed"** means the material is taught in your course and is fair game for the final exam or similar cumulative assessment. (If your course doesn't include a final exam, think about what it would include hypothetically.)

[1] We acknowledge that the list of topics is heavy on quantum computing and communication, even though the field of QIS is much broader (encompassing e.g., quantum sensing). This was an intentional design choice informed by our group's prior knowledge of QIS education in the US (e.g. [3, 19]) and an ongoing study of university course catalogs occurring at the time of survey development [30]. This list, we emphasize, is not a value judgment on whether these topics are the "right" topics to teach. We take the low percentage of courses that reported discussing quantum sensing and metrology (22%), along with the overall lack of responses to an open-ended question at the end of the survey asking if specific topics had been missed, as evidence that our survey scope was appropriately comprehensive for the type of course we wished to investigate.

- **"Covered but not assessed"** means you discuss the topic in class but it would not be appropriate for a final exam. This might include material that is discussed briefly or hand-wavily, or that is tangential to the primary goals of the course.

2.2 Survey distribution

Links to the survey were distributed over email to 449 faculty identified as teaching possible or probable QIS courses at U.S. institutions in the 2019-20, 2020-21, 2021-22, or 2022-23 academic years. Such QIS courses were identified via a thorough search of the course catalogs and associated databases of 475 institutions in fall 2022 [30]. The 475 institutions searched were selected based on quantity of degrees granted in QIS-adjacent fields. Institutions were included provided that they met one of the following criteria for at least one QIS-related field (physics, computer science, or electrical and/or computer engineering) in 2021:

- Top 100 bachelor's degree-granting program in field, and/or awarded 50 or more bachelor's degrees in field
- Top 50 master's degree-granting program in field, and/or awarded 15 or more master's degrees in field
- Top 50 Ph.D.-granting program in field, and/or awarded 10 or more research-based Ph.D.'s in field

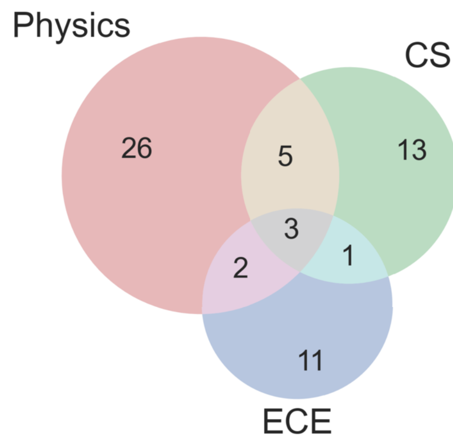
Email addresses were located for each faculty member identified as an instructor of one of the potential QIS courses identified from this search wherever possible. Email contacts do not necessarily correspond 1:1 with courses since a small number of instructors taught more than one course while a sizable number of courses were taught by multiple instructors. A small number of instructors (4) were added to the list because they had previously been identified as teaching QIS content via a similar but more limited study of course catalogs from 2019-20 [3]. Email recipients were encouraged to forward the survey to any other faculty teaching QIS courses they were aware of. The survey was open for approximately 6 weeks in September–October 2022; two follow-up reminder emails were sent during this period. We received a total of $N = 85$ substantially complete responses which we analyze in this article.

2.3 Identifying introductory QIS courses

For curriculum and assessment development purposes alike, a useful categorization is the "introduction to QIS" course, a subset of $N = 63$ responses corresponding to introductory QIS courses at the undergraduate and/or graduate level. As in Ref. [19], we define introductory QIS courses as those that focus on theory of quantum information technologies and/or quantum computing and that require no prerequisite QIS courses or domain-specific experience. Our definition excludes courses primarily focused on laboratory work or on materials/hardware development, though it includes courses that include QIS theory and another topic (e.g. quantum optics) as co-equal foci. Whether a course was classified as intro to QIS was determined primarily by self-classification; instructors could self-select one or more of the following:

- Introduction to QIS/quantum computing (primarily focused on theory and/or programming)
- Introduction to QIS/quantum computing + an additional topic (e.g. quantum information + quantum optics)

Figure 2 Catalog listings by discipline, including cross-listings, for each of the $N = 63$ introductory QIS courses we discuss in this article. Note that $N = 2$ courses are listed in none of these primary disciplines



- Hardware/materials course primarily focused on device fabrication or quantum hardware
- Beyond introductory QIS course (students expected to have already taken 1 or more dedicated QIS courses and/or have prior familiarity from research)
- Traditional quantum mechanics course, some QIS content
- Traditional computer science course, some QIS content
- Lab course or practicum
- Other/explain (free response)

The categories listed above were developed from responses to the 2021 survey [19] as well as analysis of course descriptions found via the catalog search. If an instructor selected either or both of the first two options (and no other option), the course was automatically coded as introduction to QIS. Our team manually coded courses for which the instructor selected multiple options and/or "other/explain." Example "other/explain" responses classified as intro to QIS:

- *"Half quantum software and half hardware after intro to QM [quantum mechanics]"*
- *"Graduate introduction to quantum information and computing requiring graduate QM but no previous QI[S] experience"*

Example responses not coded as introduction to QIS:

- *"Mix of intro QM, quantum chemistry, DFT, supercomputing, and QIS/quantum computing"* (too broad)
- *"Studying cryptosystems which are/aren't secure in a quantum computing environment"* (advanced subtopic)

We focus on the $N = 63$ courses coded by our team as introduction to QIS for the remainder of the paper. A breakdown of these courses by academic discipline is shown in Fig. 2.

2.4 Limitations

While our survey results represent the most diverse cross-section of QIS coursework in the US we are aware of in the literature, our survey results should be considered in light of a few key structural limitations. While we attempted to devise as complete a list of QIS courses as practically feasible when generating our instructor email list, assumptions made in the identification of courses may bias results in favor of instructors at certain institutions. Our dataset is restricted to 4-year institutions and does not reflect the experiences of instructors at 2-year colleges and pre-college programs, an audience that recent work argues has historically been underrepresented in the deployment of QIS educational initiatives [12]. (Of course, some instructors not on our email list may have received the survey forwarded from colleagues.)

Additionally—reflecting the lack of diversity in QIS education—our survey respondents were disproportionately white/Caucasian (82% of those choosing to respond) and male (81%). Respondents from large 4-year universities were also overrepresented in the dataset, consistent with prior work [3]: of the $N = 59$ courses for which instructors submitted data on the institution where the course was taught, 43 (73%) hailed from R1 research institutions and only $N = 8$ (14%) from non-doctoral-granting institutions. Approximately 75% of courses were from publicly-funded institutions.

Finally, results may have been impacted by a pair of survey design anomalies. First, a Qualtrics glitch caused submissions for multiple courses in the same survey session to overwrite responses for prior courses, risking data loss. The survey was briefly re-opened in November 2022 to enable affected respondents to submit missing data; only one such response was submitted during this window. Since we expected a large majority of faculty to submit only a single response, we believe the glitch's effect on our data was small.

A second anomaly affected mathematical subtopics. The survey used Qualtrics display logic to automatically skip subtopic questions if the instructor selected "covered minimally or not at all" for the associated umbrella topic. However, the umbrella topic "Mathematical Foundations of QIS" appears to have been interpreted by some faculty as corresponding to a much greater mathematical sophistication than the research team anticipated.[2] As designed, the survey automatically skipped all math subtopics for 5 instructors who selected "covered minimally or not at all" for "mathematical foundations of QIS"; however, these 5 faculty's responses elsewhere in the survey are inconsistent with a math-free course. For this reason, math subtopics are reported as percentages only out of the $N = 58$ courses whose instructors were explicitly shown these subtopics.

3 Analysis and key findings

For **RQ #1-3**, we collapse the categories of "covered and assessed" and "covered but not assessed" as both levels of coverage are generally suitable for curricular materials development and for comparative analysis of curricula. We also include "reviewed (assume prior knowledge)" in the collapsed category because QIS instructors often have to spend substantial time on foundational mathematics and physics content even if it has been ostensibly seen in prerequisite courses [19], and reviewed material often must nevertheless be (re)learned independently outside of lecture. For **RQ #4** we collapse only "covered and assessed" and "reviewed (assume prior knowledge)," as discussed in Sect. 3.4.

A complete list of topics and subtopics, ordered by the percentage of courses covering them, is provided in Table 1. We discuss specific findings below by research question.

[2]For example, all 5 responses that selected "cover minimally or not at all" for mathematical foundations also selected "covered and assessed" for specific algorithms or communication protocols that would be extremely difficult to teach without linear algebra and bra-ket notation. Moreover, 2 of the 3 responses that selected "covered but not assessed" for "mathematical foundations of QIS" then marked "covered and assessed" for a large proportion of the math subtopics.

Table 1 Full survey results for introductory QIS courses at the postsecondary level ($N = 63$ courses). Bolded percentages reflect those topics covered in $\geq 80\%$ of courses. *Topics also meeting the stricter threshold of being *assessed* in $\geq 80\%$ of courses (see Sect. 3.4). †Percentages for mathematics subtopics are reported only for the $N = 58$ responses shown full list of subtopics (see Sect. 2.4). ^Topics we had *a priori* reason to believe were probably covered in only a minority of intro QIS courses; these topics were still shown to all survey respondents as a sanity check

Topic	% Covered	Topic	% Covered	Topic	% Covered
Qubits*	**100%**	**Math foundations QIS*†**	**(92%)**	**Physical implementations**	*71%*
Entanglement*	**100%**	Dirac notation (bra-ket)*	**100**	Superconducting qubits	*57*
Superposition*	**98%**	Complex numbers*	**100**	Trapped ions	*57*
Quantum gates*	**98%**	Unitary matrices*	**100**	Photonics	*44*
CNOT*	**98**	Inner product*	**98**	Neutral atoms	*25*
Hadamard (H)*	**98**	Dim. of Hilbert space*	**97**	Nitrogen vacancy centers	*24*
Identity (I)*	**98**	Vector spaces, finite dim.*	**93**	Other implementation(s)	*11*
Pauli X*	**98**	Tensor/Kronecker product*	**93**	**QIS theory (uncategorized)**	–
Pauli Z*	**98**	Hermitian matrices	**93**	No cloning theorem	**95**
Pauli Y*	**97**	Eigenvalues/eigenvectors*	**91**	EPR paradox	**81**
Phase gate (S, T)	**92**	Outer product	**86**	Bell inequalities	*75*
SWAP	**89**	Matrix exponential	*79*	Decoherence, noise channels	*73*
CZ	**89**	Commutators	*66*	Quantum error corr. codes	*71*
Universality of gates	**89**	Vector spaces, infinite dim.	*43*	Heisenberg uncertainty	*65*
Toffoli (CCNOT)	**84**	Number theory	*40*	Open quantum systems	*56*
Other 2+ qubit gate(s)	*68*	Combinatorics	*31*	Complexity classes	*49*
Quantum algorithms*	**98%**	**Quantum comm./cryptog.***	**87%**	**Presumed advanced topics^**	–
Deutsch/Deutsch–Jozsa*	**90**	Quantum teleportation	**81**	Density matrix/mixed states	*68*
Grover search algorithm	**87**	Quantum key dist. (BB84)	*70*	Coherence time (T1, T2)	*38*
Quantum Fourier transform	**87**	Superdense coding	*60*	State fidelity	*37*
Shor's factoring algorithm	*79*	Quantum key dist. (E91)	*30*	Quantifying entanglement	*35*
Simon's problem	*62*	Quantum key dist. (B92)	*27*	Entropy (von Neumann)	*33*
Bernstein–Vazirani	*56*	Quantum key dist. (other)	*3*	Entropy (Shannon)	*33*
Phase estimation subroutine	*52*	**Bloch sphere**	**84%**	Adiabatic QC	*29*
Quantum machine learning	*17*			Measurement-based QC	*24*
Other algorithm(s)	*13*			Quantum sensing/metrology	*22*
Quantum measurement*	**97%**			Quantum optics	*19*
Quantum circuit diagrams	**97%**			Quantum compilers	*17*
				Topological QC	*14*
				Post-quantum classical cryptography	*11*

3.1 RQ #1: core curriculum for curriculum development

We identify a core set of topics that appear to be shared across a large majority ($\geq 80\%$) of introductory QIS courses and that represent foundational skills and concepts that can be effectively targeted for curriculum development (listed here, and bolded in Table 1):

- **Qubits**
- **Entanglement**
- **Superposition**
- **Quantum gates** (including most well-known gates and the concept of quantum gate universality)
- **Quantum algorithms** (specifically Deutsch–Jozsa, Grover's search, and the Quantum Fourier Transform)
- **Quantum measurement**
- **Quantum circuit diagrams**
- **Quantum communication and cryptography** (specifically quantum teleportation)
- **Bloch sphere**
- **Certain mathematical skills**: Dirac notation, complex numbers, finite-dimensional Hilbert spaces and their dimension, unitary and Hermitian matrices, inner/outer/tensor products, and eigenvalues/eigenvectors
- **Uncategorized QIS theory topics**: no cloning theorem, EPR paradox

Table 2 Topics for which a statistically significant difference ($p_{\mathrm{adj}} < 0.05$) was observed in coverage between undergraduate and graduate introduction to QIS courses. $N = 63$ courses: $N_U = 46$ listed at the undergraduate level, $N_G = 39$ at the graduate level (22 listed as both)

Topic	%Undergraduate	% Graduate	p	p_{adj}
Entropy (Shannon)	26%	49%	$p < 0.001$	$p_{\mathrm{adj}} < 0.001$
Density matrices/mixed states	63%	82%	$p = 0.002$	$p_{\mathrm{adj}} = 0.004$
Entropy (von Neumann)	26%	44%	$p = 0.011$	$p_{\mathrm{adj}} = 0.033$

Note that the 80% threshold was chosen empirically (see Table 1 exhibiting a visible gap in reported percentages near this threshold) as a first-order partition of the surveyed content for curriculum development. Readers are encouraged to apply a higher or lower threshold as appropriate to their work and should interpret the percentages reported in Table 1 accordingly.

3.2 RQ #2: comparing undergraduate and graduate courses

Few meaningful differences were observed between undergraduate and graduate courses in terms of content coverage. Only for the three advanced topics shown in Table 2 were statistically significant differences detected between graduate and undergraduate courses (first-order Rao–Scott[3] modified χ^2, $p_{\mathrm{adj}} < 0.05$ with Hochberg–Bonferroni adjustment[4] for multiple statistical tests). Moreover, these three advanced topics are closely related: von Neumann entropy is a basis-independent quantum extension of Shannon entropy, and mixed states and the associated mathematical tool of density matrices enable the entropy of a quantum state to be discussed quantitatively. In short, it appears that a primary distinction between undergraduate and graduate introductory QIS courses is that graduate courses are more likely to introduce the concept of mixed states and the associated information-theoretic concept of entropy. Otherwise, the percentage of undergraduate and graduate courses covering each topic were within an absolute difference of 12%, giving us confidence that our findings in Sect. 3.1 generalize across both graduate and undergraduate levels.

3.3 RQ #3: comparison of courses across disciplines

As a proxy for intended academic audience, we classified courses by catalog listing:[5] physics, computer science, electrical and/or computer engineering (ECE), or other.[6] We observed a few notable differences in content coverage across disciplines amid a general trend of cross-disciplinary uniformity. Table 3 shows topics where statistically-significant differences were detected between courses inside and outside a particular discipline (p_{adj} <

[3]Rao–Scott modified χ^2 [31] is an extension of Pearson χ^2 to multiple-response datasets, necessitated by the relatively large number of hybrid undergraduate/graduate courses (22 out of $N = 63$ courses). See Ref. [32] for an accessible breakdown of the first-order approximation applied here.

[4]The Hochberg–Bonferroni procedure is designed to compensate for the risk of incorrectly rejecting the null hypothesis (Type I error) given repeated statistical tests while retaining greater statistical power than the conservative Holm–Bonferroni adjustment [33]. Holm–Bonferroni is designed to strictly control Type I error (false positives) but can lead to high rates of Type II error (false negatives) for datasets with few significant variables. For our exploratory purposes, we judge Type II error of comparable concern to Type I error so a less strict, though still conservative, adjustment is warranted.

[5]We recognize that per Ref. [19], course catalog listing does not always correlate well with the actual breakdown of the students in a QIS course; however, we take catalog listing as a useful indicator of the audience(s) most explicitly being targeted.

[6]Physics includes engineering physics. ECE includes one transdisciplinary program encompassing several engineering subfields, electrical among them.

Table 3 Topics for which a statistically significant difference ($p_{\mathrm{adj}} < 0.05$) was observed in coverage across disciplines. $N = 63$ ($^*N = 58$) courses: $N_{\mathrm{Phys}} = 36$ (32) listed in physics or engineering physics, $N_{\mathrm{CS}} = 22$ (20) listed in computer science, $N_{\mathrm{ECE}} = 17$ (17) listed in ECE

Topic	%CS	%NotCS	p	p_{adj}
Commutators*	30%	84%	$p < 0.001$	$p_{\mathrm{adj}} < 0.001$
Quantum sensing & metrology	0%	34%	$p = 0.001$	$p_{\mathrm{adj}} = 0.002$
Density matrices/mixed states	41%	83%	$p = 0.001$	$p_{\mathrm{adj}} = 0.004$
Outer product*	65%	97%	$p = 0.002$	$p_{\mathrm{adj}} = 0.006$
Shor's factoring algorithm	100%	68%	$p = 0.002$	$p_{\mathrm{adj}} = 0.012$
Topic	%Physics	%NotPhysics	p	p_{adj}
Deutsch (or Deutsch–Jozsa) algorithm	100%	78%	$p = 0.004$	$p_{\mathrm{adj}} = 0.026$
Quantum error correcting codes	86%	52%	$p = 0.005$	$p_{\mathrm{adj}} = 0.032$

0.05, Fisher's exact[7] with Hochberg–Bonferroni adjustment). No significant differences were found between ECE and non-ECE courses, though this may be an artifact of small sample size ($N_{\mathrm{ECE}} = 17$).

Computer science courses disproportionately taught Shor's factoring algorithm (100% of CS-listed courses, 68% of non-CS courses). We hypothesize that CS instructors may place greater value on the explicit connections between quantum computing and integer factoring (which is a problem of specific importance to cybersecurity) than physicists and electrical engineers. Indeed, no significant difference ($p = .24$, Fisher's exact) is observed in CS vs. non-CS coverage of the quantum Fourier transform—the core quantum subroutine of Shor's algorithm—suggesting that the underlying distinction is in treatment of the classical subroutines linking the quantum Fourier transform to factoring. Additionally, computer science courses were disproportionately likely *not* to teach commutators, outer products, density matrices/mixed states, and quantum sensing/metrology—all topics of great interest to quantum information theory and the physical construction and characterization of quantum technologies but with fewer direct connections to quantum algorithms. Finally, two topics—Deutsch's algorithm and quantum error correcting codes—were statistically more likely to be taught in physics than in non-physics courses, for reasons the authors can only speculate on.

3.4 RQ #4: implications for research-based QIS assessment

Research-based conceptual assessments such as the Force Concept Inventory [34] have historically been powerful DBER tools, with benefits ranging from helping educators improve their teaching methods via reliable comparisons across instructors and institutions to validating research-based curricular materials [35]. In 2021, 34 prominent leaders in quantum research and education called for emerging QIS education programs to commit to utilizing research-based assessments from the DBER community from the beginning so as to identify and promulgate best practices [18]. While a number of research-based quantum mechanics assessments have been developed [36–42], it is our group's experience that none appears particularly well-aligned with the goals and content emphases of

[7] Unlike Sect. 3.2, we apply Fisher's exact test here because a large proportion of contingency tables violate the assumptions of a χ^2 test due to small expected counts. (On the other hand, we know of no accessible procedure for expanding Fisher's exact to multiple-response datasets, motivating the use of Rao–Scott modified χ^2 in Sect. 3.2 where expected counts were sufficiently large to justify using a non-exact test.)

a typical introductory QIS course.[8] Since a new assessment instrument targeting postsecondary introductory QIS courses may be warranted, we find it useful to compile a more specific list comprising those subset of topics that instructors *assess* in their courses.

For assessment purposes, we collapse only the categories of "covered and assessed" and "reviewed (assume prior knowledge)" in order to preserve the covered/assessed distinction. Those topics that met an 80% *assessability* threshold are indicated in Table 1 by an asterisk.[9] While instructor reports of what material is assessed in there classes are a useful starting point, we emphasize that not all topics included on this list will ultimately be appropriate for inclusion on a research-based QIS assessment. Formulating actionable assessment objectives is itself an involved, iterative procedure [44] beyond the scope of this paper that we anticipate will winnow our list of topics significantly as some topics (e.g. quantum gates) are more readily translated to assessment objectives than others (e.g. Deutsch's algorithm).

4 Discussion and conclusions

There is much ongoing dialogue in the community as to the evolving goals of QIS education and quantum workforce development, especially in terms of academia-industry alignment[10] [11, 18, 26, 46]. As mentioned in the Introduction, prior studies aiming to define the scope of QIS education [24–26] have largely focused on what *ought* to be taught rather than what *is* currently being taught; disentangling the two is undeniably important if we are to make informed decisions about what to teach moving forward.

It is noteworthy, then, that the core ideas of quantum computing identified in Ref. [24] correspond quite strongly to the umbrella topics we find are covered in $\geq$ 80% of the intro QIS courses we surveyed: Superposition, entanglement, quantum algorithms, and quantum communication. Our presumed umbrella topics of qubits, quantum gates, and quantum measurement together constitute the fundamental building blocks of Seegerer *et al.*'s concept of the *quantum computer*, while our umbrella topics of mathematical foundations of QIS, quantum circuit diagrams, and the Bloch sphere represent specific representations for conceptualizing the above ideas. Meanwhile, physical implementations of quantum computing—our only presumed umbrella topic that does not map neatly to any of Seegerer *et al.*'s categories—was covered in a lower percentage of courses (71%) than any comparable topic. Seegerer *et al.* present their findings as investigating QIS education from a computer science perspective; here we show that their findings can be generalized to QIS education more broadly.

We also see evidence that each discipline—physics, computer science, and ECE—has a unique perspective on QIS education, a theme we previously observed in Ref. [19]. In fact, the disproportionate number of CS-specific differences we observe seem to confirm Seegerer *et al.*'s contention that a CS-specific perspective on QIS education may exist. (Perhaps the CS perspective is best identified by the focus on software and algorithms over hardware, in which case the absence of physical implementations from Seegerer *et*

[8] Existing assessments have a heavy focus on wave functions and on computing expectation values of physical observables, topics emphasized in traditional physics Quantum 1 courses, but less so in QIS and especially quantum computing contexts. See e.g. Ref. [43] for an overview of existing quantum assessments.

[9] The 80% assessability threshold, like the curriculum development threshold, was chosen empirically based on visual analysis of the data.

[10] The European Competence Framework for Quantum Technologies [45, 46] may serve as a useful model of academia-industry alignment if such alignment is indeed what is sought by the US QIS education community.

al.'s five core ideas of QIS education is unsurprising). Nevertheless, on the whole, we find that similarities in content converge across disciplines far outnumber differences. We see the convergence of these curricula across disciplines, along with the sizable number of cross-listed courses, as evidence that a core QIS curriculum is coalescing even in the face of the widespread variation in learning goals and instructor backgrounds we observed in 2021 [19].

As outlined in Sect. 3.1 and shown in Table 1, we find that certain topics are covered in a large majority ($\geq 80\%$) of introductory QIS courses and as such make ideal targets for developers of research-based curricular materials. A similar list is developed for assessment. While introductory QIS courses may vary in terms of what advanced topics may be covered, there remains a common set of foundational math and physics concepts that undergird these higher-level topics. In prior work [19], tensor products and eigenvalues/eigenvectors emerged as particular sites of instructor-perceived difficulty for students, so these two topics may be ideal starting points for curriculum development. Alternatively, tutorials breaking down the most commonly taught quantum algorithms—Deutsch–Jozsa, Grover's search, and the Quantum Fourier Transform—into conceptually digestible pieces may also prove valuable since these algorithms require synthesizing many distinct and challenging concepts encountered throughout the course.

5 Guidance and future work

Over the past few years, DBER communities have begun heeding the community's calls for research-based curriculum development [17, 18], creating QIS education materials for a variety of contexts (e.g. [47]). However, such work has been relatively specialized, often focusing on teaching quantum computing to high school students [48–50] and developing simulation resources [51, 52]. We urge the community to broaden our focus to span more areas of QIS theory, especially those identified as consensus areas in this article. We also suggest building on curriculum development projects such as QuSTEAM [53] and Qubit by Qubit [54] that center needs of historically underrepresented students. We likewise call on the community to place greater emphasis on fundamental research in QIS student reasoning (e.g. [55, 56]), which can serve to scaffold future curriculum development initiatives.

Finally, we reiterate that the core content list we have developed here is just one intermediary step toward the development of research-based curricular materials or assessment items. Our future work will build upon this list of core content to formulate measurable learning outcomes for development and validation of curricular materials. (The Quantum Curriculum Transformation Framework [57] provides a useful framework for subsequently translating these learning outcomes into effective curricula.) Separately, we have begun to use the list compiled in Sect. 3.4 to develop objectives and draft assessment items for a research-based postsecondary QIS assessment,[11] which based on the findings in Table 1 will most likely emphasize quantum computing.[12]

[11] While our work targets the introductory undergraduate/graduate audience, an EU-based collaboration is developing a parallel assessment instrument for high school students [58].

[12] Standard statistical validation using classical test theory (CTT) requires maintaining a static assessment form, thus demanding a high degree of instructor agreement on content coverage if the assessment is to see real-world uptake in courses. In the longer term, topics such as quantum communication and quantum sensing might well be appropriate for inclusion on next-generation flexible assessments [59].

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Data availability
The datasets generated and/or analysed during the current study are not publicly available due to identifiable human subjects data, but can be made available (with necessary redactions) from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Author contributions
JCM developed the first draft of the survey and performed the majority of the data collection, analysis, and writing with input and guidance from GP, SJP, and BRW. All authors contributed considerably to the design and content of the survey instrument as well as the formulation of research questions. All authors have read, contributed to, and approved the final manuscript.

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