# Creating a modular, workforce-relevant undergraduate curriculum for quantum information science and engineering for all people

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Recently, the "second quantum revolution" has been identified as crucial for technical innovation and a potential driver for workforce development and economic growth in the United States and beyond. However, there is a severe workforce shortage in the Quantum Information Science and Engineering (QISE) domain. QISE sits at the intersection of many fields, and there is no universally agreed-upon curriculum for it. It is thus necessary to produce an inter-disciplinary curriculum for QISE, which not only trains future smart workforce, but also makes sure that the workforce is diverse (e.g., in terms of gender and ethnicity). Our interdisciplinary team, including education researchers and content experts from across STEM, arts, and other disciplines, aims to fill this important gap by creating a modular, industry-connected curriculum called QuSTEAM. The modular nature of the curriculum will allow content to be applied at various institutions (e.g., R-1, community colleges, and HBCUs) in a seamless manner.

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## I. INTRODUCTION

The National Science and Technology Council and President's Council of Advisors on Science have identified Quantum Information Science and Engineering (QISE) as a key area for technical innovation with the potential to drive new job creation and economic progress [1], [2]. However, these opportunities can only be realized with a quantum smart workforce capable of capitalizing on them. Given the pace and scope of the Quantum Leap, meeting this challenge will require both retention of existing STEM graduates and the training of new scientists and engineers. While there are a few graduate programs in the field of QISE due to the shift in federally funded research, there are only a handful of educational programs at the baccalaureate and associate's level. These include a baccalaureate program at the University of Chicago [3], a pioneering high-school education project by Qubit by Qubit [4], and ongoing efforts by private companies such as IBM and Google [5] to make quantum computers accessible and comprehensible. These efforts, while individually innovative, are largely confined to the development of isolated elective courses within (with the exception of the University of Chicago) and as a result are not capable of meeting the scale of demand that is emerging.

A 2018 study by Pew Research [6] found that 35% of the STEM workforce do not have a B.S. and 71% do not have a Postgraduate degree. STEM broadly is, of course, different from QISE. However, a query of the jobs page at the Quantum Economic Consortium in 2021 revealed that only 41% of the positions listed required an M.S. or Ph. D., indicating that the trend of requiring a significant workforce at or below the B.S. level may continue in the field of QISE. Making a substantial impact on the workforce demand will require a coordinated effort across many universities

Our team is developing an innovative solution to create a modular curriculum for QISE at the baccalaureate and associate's level. Our team consists of academics, both subject matter experts (SME) and discipline-based education researchers (DBERs). We have brought together academic faculty, students, and industry practitioners to meet the needs of a diverse set of students and employers.

The purpose of this curricular initiative paper is to summarize the early findings and processes of the QuSTEAM project. To ensure that we create a robust curriculum that meets the demands of industry and academia, we have conducted thorough needs finding with our stakeholders (students, industry, and academia). We briefly discuss results from our needs finding phase and how these findings are being used to inform the curriculum development process. Finally, we provide an example module that our team is preparing and delivering. We also provide a brief framework and strategy on how we are planning to proceed with creating a minor in QISE.

## II. QUSTEAM PROJECT

To develop an interdisciplinary and inclusive QISE curriculum, we have assembled a team of 66 faculty from five research intensive R-1 institutions, six community colleges proximal to those R-1 institutions with a history of collaboration, and from a consortium of more than twenty historically black colleges and universities (HBCUs). The team includes SMEs and DBERs that combine breadth of disciplinary expertise with established success in the development and assessment of research-based STEM pedagogy. Having the perspectives and needs of so many departments and institution types ensures that the resulting curriculum can be implemented nationally in several different educational contexts. The core set of institutional participants includes The Ohio State University, the University of Chicago, the University of Illinois, Michigan State University, and North Carolina A&T.

Our team recognizes that historically marginalized and minoritized communities in STEM are inherently valuable and that their oppression is a cost to us individually and as a society [7]. The QuSTEAM team is committed to acknowledging the value that diverse groups bring to the curriculum development and delivery process and are actively engaging these groups in all stages of the process [8]. This engagement includes core team membership, outside review, target audience members, and participation in needs finding.

The QuSTEAM curriculum will have a modular format with in-person, online, and hybrid delivery modalities to meet the educational needs of a diverse set of institutions and stakeholders. These include current and future quantum professionals, community colleges, minority-serving institutions (MSI), and other B.S. and Ph. D.-granting institutions. We will draw on the extensive expertise of the core participants in both quantum research and STEAM education to create a new curriculum with multiple implementations at the major, minor, and certificate level. Absolute modularity is clearly not possible; all learning builds on previous learning. But it is possible to introduce or recapitulate hyper-focused areas of mathematics, physics, economics, etc, relevant to a topic within that topic's module. This can be used to reduce prerequisites and reach interesting, major-relevant material earlier in the curriculum than in many STEM fields (thereby reducing attrition [9]). The curriculum will be piloted at participating institutions, drawing on a total undergraduate student body of over 230,000 from the geographically proximal northern midwestern region of the U.S. This balance of scope and geographic proximity will allow for effective leveraging of local partnerships with industry and national labs while demonstrating the ability to train a quantum smart workforce at the scale necessary to support economic development. This scale also facilitates drawing expertise from multiple institutions in the classroom; students will have access to world-leading experts in QuSTEAM relevant disciplines. This can be sustainable using hybrid and virtual on-line modalities that pair experts and students from multiple institutions, providing a unique teaching and learning ecosystem. This mode of delivery is increasingly relevant and impactful given the accelerating shift towards hybrid and online instruction driven by the need to implement social distancing in educational environments [10]. This approach is also critical for enabling quality QISE education at smaller institutions that may not have sufficient expertise in-house.

Traditional STEM content and pedagogy incorporates few if any elements of arts and humanities. However, it is increasingly important to incorporate arts in STEM curriculum [11]. This is especially true, given the goal of increasing the size of the quantum-smart workforce, and its diversity. For this purpose, QuSTEAM is integrating arts and humanities from the outset, thus, resulting in an engaging, innovative, inclusive, and student-centered educational experience.

Building a robust curriculum is not sufficient for systemic change and high-quality instruction. It is also necessary for the instructors to employ research-based STEM instructional methods and especially embed inclusive teaching techniques and mindsets in every aspect of the instruction and climate. Therefore, a substantial part of our effort will include engaging instructors in professional development and providing instructional notes in the curricular materials.

## III. EARLY FINDINGS AND PROCESSES

During Spring 2021, the DBER team of the QuSTEAM project conducted needs finding using focus groups with undergraduate and graduate students, faculty, and industry practitioners. Before engaging with our stakeholders, we conducted a pilot with our team members and collaborators to create and revise three different semi-structured interview protocols, one for each type of stakeholder.

A combination of convenience and snowball sampling was used to recruit participants [12]. Prospective student participants were identified through initial outreach to collaborators and department chairs, with the request that our solicitation be forwarded to students who had shown an interest in QISE or quantum mechanics, in general. Student participants were invited to answer a very brief survey covering their interest in QISE, their background, and demographics. These data allowed us to select the final interview pool to reflect a diverse set of learners, including a range of different majors/fields, races, genders, ethnicities, and various levels of progress toward their degree. From an initial pool of 137 students, 12 students were selected into two focus groups having high diversity along these multiple axes. The recruitment strategy for faculty and industry was initially the same, but the pools resulting from the initial surveys were much smaller (11 faculty and 9 industry practitioners). Further, the pools were not sufficiently diverse to reflect the needs and values of all institutions and historically minoritized groups, which led to additional rounds of recruitment.

### A. Results of needs finding

The needs finding process revealed themes that were common across all groups. Here, we discuss a few themes common to all three stakeholder groups, before looking at differences between the groups.

***Teaching QISE without unnecessary prerequisites:*** All groups suggested that a qualitative overview of principal features of QISE is possible without requiring prerequisites in linear algebra or higher mathematics. Groups suggested that a qualitative understanding of superposition, entanglement, and QISE applications could be made tractable for students of varied backgrounds in mathematics. This often emerged only after debate. For instance, one instructor suggested, *"We need rigorous understanding of probability amplitude vs. classical."* Another instructor responded by saying: *"I'm not sure about that. I think we can do a lot of this using conceptual analogies."* The latter instructor went on to describe how many classical mechanics concepts can be sidestepped in the interest of focusing on the “information” part of QISE, and less on the typical content of a quantum mechanics course.

***Skills required for QISE:*** All groups agreed that there are skills unrelated to the content that are crucial for students to learn. These skills included coding in one or more programming languages, teamwork, project management, and communication. Some participants specifically emphasized teamwork and communication because QISE sits at the nexus of multiple fields, and no one is likely to be an expert in all of them. One faculty member stated, “They need to be able to talk to people in other disciplines.” Another faculty member focused on the need for a shared vernacular: “We want students to understand the vocabulary around quantum computation, simulation, and sensing.” This idea was also echoed by industry practitioners: “The biggest challenge is language, terminology, getting comfortable having conversations."

TABLE I. Differences among stakeholders.

| Emphasis | Students | Industry | Faculty |
|---|---|---|---|
| Math, linear algebra | | | x |
| Communication, curiosity, passion | x | x | |
| Entanglement, superpose., prob. | | x | x |
| Employability and job placement | x | | |
| Hands-on training in lab courses | | | x |

***Engagement with industry:*** All groups further emphasized engagement with industry. QISE is new enough that it is not always clear where the jobs will be, and ensuring students have a clear path to employment will be critical both to student retention, and to their success upon program completion. All groups also agreed that diversity is a priority, especially since QISE is emerging from fields that all suffer from poor diversity. One student commented on the importance of seeing and engaging with students and mentors with backgrounds and demographics like your own: *"I mean, I think it's super important. Like, I definitely feel a lot more supported when there are other women in my classes. And I've definitely formed close relationships with a lot of the women professors at my school."*

Some themes were more apparent in one group than another. For example, undergraduate students were interested in the QISE field, even though they do not really know much about it. One student stated: *"Quantum becomes important as things get smaller and smaller, so that soon we can't improve computers without worrying about quantum."* While this statement is not incorrect, it suggests a conflation of the breakdown of Moore's Law and using quantum mechanics for information processing. Students and industry practitioners were vocal about the need for people with a minor in QISE, arguing that there is a need for people with a shared vernacular of quantum mechanics, who have an overview of what is possible in QISE, but still have the more traditional skills of, for example, physics, marketing, or computer science.

In addition to common themes, it is important to discuss where the three groups of stakeholders diverge in their thinking and perceptions about a potential QISE degree. For instance, students and industry practitioners emphasized on the importance of communication, curiosity, and passion. Whereas these traits were not mentioned by faculty. Table 1 shows how themes diverged among the three different stakeholders. This description of themes is not exhaustive. Additional themes and results of needs finding will be discussed in subsequent publications.

### B. Structure of the QuSTEAM curriculum

It emerged from industry and student focus groups that their needs would be optimally met by designing a QISE minor. For developing courses in the minor, we are using the backward design process [13], and evidence-based techniques [14] to assess courses in the minor. From a three-person distillation of stakeholder priorities, we identified four key facets that would guide the development of courses in the QuSTEAM curriculum. Sample learning goals for each facet of the curriculum are given below:

1. *Basic concepts and phenomena in QISE:* Construct and critique simple models and analogies through creative works.
2. *Applications of QISE concepts:* For a given context predict whether a quantum device beats a classical device and explain why.
3. *Societal Impact:* Construct evidence-based arguments for both positive and negative societal impacts of QISE technology development.
4. *Professional Development:* Demonstrate the ability to work in an interdisciplinary team, and an understanding of professional communication of technical concepts.

Each module in the curriculum will be developed and assessed by a team of faculty and industry partners. Each team will reflect diversity in backgrounds, including representation of multiple QISE-related fields, and representation of different types of institutions.

## IV. EXAMPLE MODEL CURRICULUM

Consider the example of a 3-week module titled "Quantization and States." This module will be piloted in Fall 2022 at a large midwestern university. The goal is for students to understand quantization and how the quantum mechanical world differs from the classical world. This module will provide students with enough grounding to become familiar with the concept of states, which will act as the prerequisite to future modules. Table 2 provides outlines how we apply the framework we have discussed to develop various activities of this module. Once the module is pilot tested and revised, it could potentially be integrated in a semester-level course in the QuSTEAM Curriculum.

TABLE II. Sample learning goals and activities for a module on ‘quantization and states’

| | | | |
|---|---|---|---|
| Learning and Skill-Development Goal | (A) Students will explain several differences between the classical and quantum world, including quantization and superposition in multiple contexts (Facet 1). | (B) Student teams will model phenomena. This involves ensuring all team members are active, included, and valued (Facet 2 & 4). | (C) Students will see the role of some computing structures (such as for loops or random number generators) and make minor modifications to achieve a desired effect (Facet 1, 2, and 4). |
| Acceptable Evidence of achievement | (A) Students describe the outcome of a classical Stern Gerlach (SG) experiment, and the quantum SG experiment. Students could predict the outcomes when several SG measurements are performed in sequence. Students correctly describe the results as probabilistic. | (B) Students can share responsibility in a group experiment. All students speak, collect data, and report afterwards that their voices were heard and were valued. | (C) Students modify existing code in Jupyter notebooks simulating the SG experiment to achieve minor experimental variation, for example by changing the number of particles used, the initial states of the particles, etc. |
| Example Activities | Students will carry out a classical SG experiment using small bar magnets launched through a region of inhomogeneous magnetic field. They will make predictions, then make experimental observations. Students will work as a team (B) to build a model to explain these observations (A). Students will test their model by altering something about the experimental setup (bar magnet dimensions, inhomogeneous field strength, using non-magnetic “particles”). Students will repeat the process for the quantum SG experiment (A). The experiment will be carried out using remote instrument control or using simulations. Part of testing their model will be modifying simple code in Jupyter notebooks to replicate simulations (C). | | |

## V. CONTINUING AND FUTURE WORK

In the 2022-2023 academic year, the team will teach and revise a set of four core and two elective courses in QISE minor. Each course is developed/revised by a team consisting of SMEs and DBERs from various academic institutions. Since this project is ongoing, we are presenting a preliminary description of the four core courses in the QISE minor. The course titles and descriptions are likely to evolve over the course of this project. The four core courses are: Quantum Information: The Second Quantum Revolution, Classical vs. Quantum Logic, Information Systems, and Classical and Quantum Laboratory. A brief description of these is given below. Data will be collected from these courses on student resources, content mastery, and on attitudinal and motivational factors.

*Quantum Information: The Second Quantum Revolution:* An introduction to QISE for 1st year students from a wide range of majors, even outside of STEM. Students will engage with critically reason about basic QISE phenomena, concepts, technological applications, and potential societal impacts (e.g., superposition, entanglement, and cryptography, and communications) via simulations, physical demonstrations, simple models, and analogies, with a light introduction to simple aspects of the formalization of these ideas and methods.

*Classical vs. Quantum Logic:* This second-semester course will build on the first semester introduction to QISE and make use of similar computing tools. Students will first learn the formal logical structures that underlie both classical and quantum computing, and then implement these structures in Python.

*Information Systems:* This class will ensure students are able to describe quantum systems using linear algebra, and inversely, describe the physical meaning of a linear algebraic operations and entities.

*Classical and Quantum Laboratory:* In this hybrid class students will (1) learn how to identify sources of error, noise, as well as identify the requisite steps to minimize and work around these issues, (2) learn remote instrument control to run experiments at partner institutions, (3) perform measurements on a qubit.

All four mandatory courses require either no or minimal prerequisite knowledge in mathematics. Some of these modules will also be more computationally driven (e.g., learning programming for quantum computing, simulation of a quantum computer, and interaction with real quantum computers, logging into IBM Q to execute code). The elective courses include Quantum information systems and Quantum software. Once these courses have been developed and pilot tested, they will also be offered at our partner institutions and beyond.

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