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Building a Quantum Engineering Undergraduate Program

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Abstract—Contribution: A roadmap is provided for building a quantum engineering education program to satisfy U.S. national and international workforce needs.

Background: The rapidly growing quantum information science and engineering (QISE) industry will require both quantum-aware and quantum-proficient engineers at the bachelor's level.

Research Question: What is the best way to provide a flexible framework that can be tailored for the full academic ecosystem?

Methodology: A workshop of 480 QISE researchers from across academia, government, industry, and national laboratories was convened to draw on best practices; representative authors developed this roadmap.

Findings: 1) For quantum-aware engineers, design of a first quantum engineering course, accessible to all STEM students, is described; 2) for the education and training of quantum-proficient engineers, both a quantum engineering minor accessible to all STEM majors, and a quantum track directly integrated into individual engineering majors are detailed, requiring only three to four newly developed courses complementing existing STEM classes; 3) a conceptual QISE course for implementation at any postsecondary institution, including community colleges and military schools, is delineated; 4) QISE presents extraordinary opportunities to work toward rectifying issues of inclusivity and equity that continue to be pervasive within engineering. A plan to do so is presented, as well as how quantum engineering education offers an excellent set of education research opportunities; and 5) a hands-on training plan on quantum hardware is outlined, a key component of any quantum engineering program, with a variety of technologies, including optics, atoms and ions, cryogenic and solid-state technologies, nanofabrication, and control and readout electronics.

*Index Terms—*Quantum engineering, quantum information science (QIS), undergraduate education.

I. INTRODUCTION TO QUANTUM ENGINEERING

QUANTUM information science combines the understanding of nature at its most fundamental level—quantum mechanics—with information theory. From an applications standpoint, advancements in this field now rely on incorporating an engineering approach to better design, integrate, and scale quantum technologies. For example, the landmark quantum advantage result achieved in 2019 [1], in which a quantum computer met a computational benchmark not achievable on the same time scale with present classical computing resources, made heavy use of a range of engineering disciplines to construct a machine capable of quantum speedup. This is one example of the many recent advances in quantum information science (QIS) spanning algorithms, architectures, and qubit technologies, including atoms and ions, semiconductors, superconductors, as well as supporting hardware in integrated optics, and microwave and RF control and readout [2]–[5]. This new chapter of discovery and innovation is centered on novel devices that employ nonclassical states, superposition, and entanglement to create technological advantage over classical systems. In addition, devices based on these aspects of quantum physics could serve as a foundational technology, similar to the role of semiconductors in the 20th

century. In doing so, QIS is predicted to open up otherwise impossible vistas in communication, computation, and sensing. Future engineers are needed to address grand challenges, such as scalability and identifying unique real-world opportunities for quantum systems, and indeed industry positions reflect this need [6], [7]. Given this expectation, incorporating quantum information into formal engineering curricula will prepare students to work at the forefront of current science and technology, and drive future growth across multiple engineering sectors.

So, what is this new field of *quantum engineering* and what are the implications for education programs? As defined by the U.S. National Quantum Initiative (NQI) Act, QIS is "the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information" [8]. Building on this definition, quantum engineering is defined as the application of engineering methods and principles to quantum information systems and problems. This includes the work of both quantum-aware engineers and quantum-proficient engineers—and is necessarily redefining the field to be quantum information science and engineering (QISE).

Increasing the engineering talent flow into QISE could vastly accelerate the development of quantum technologies, some of which might be harnessed to tackle some of the world's most pressing problems, such as more efficient nitrogen fixation [9], making artificial light-harvesting photosynthetic complexes for clean energy [10], and addressing the rapidly approaching end of Moore's law and subsequent limitation on computing resources [11]. It is also a major opportunity to broaden participation in terms of diversity, equity, and inclusion. In this regard, it has been argued that modifications and innovations in the engineering portion of that pipeline, as well across the physical and computational sciences—perhaps spanning kindergarten to Ph.D. with many on-ramps and opportunities along the way—will be vital for developing the workforce necessary to capitalize on the promise of QISE. There is a pressing educational gap between, on the one hand, excitement generated both by the popular media and the increased interest in introducing QISE in the secondary school, and on the other hand, quantum-related graduate programs focused mainly on PhDs, with a few MS programs as well. This undergraduate gap can be addressed in the near term, and closing it will likely have substantial impact on the quantum workforce. Finally, many engineers traditionally do not pursue a Ph.D., but rather a Bachelor's or at most a Master's. Specializing in quantum engineering will offer a similar educational pathway to professional life as other traditional engineering disciplines with specializations, such as bioengineering. Thus, within the context of emerging quantum education activities at the K-12, Masters, and workforce upskilling levels, this article focuses its attention on the existing gap in the quantum engineering pipeline at the *undergraduate* level.

Within undergraduate programs, quantum mechanics has long been taught in physics departments, but QISE is cross-disciplinary and demands a workforce that draws from formal education programs in departments, including applied mathematics, chemistry, computer science, electrical engineering,

materials engineering, and molecular engineering, to name a few. Well-established Ph.D. programs and undergraduate physics programs must now be complemented by new efforts that broaden the population of quantum-proficient and quantum-aware scientists and engineers. This need is supported by the current demand for traditional engineering skills in quantum industry, which is well documented [12]. Thus, one of the tensions in discussing new formal education programs in QISE surrounds sufficiently training students in quantum engineering, while not overly diluting their broader engineering degree so that students retain a solid foundation for many decades of continued learning and professional experience. One needs to prepare T-shaped engineers, who have deep core knowledge and skills in some engineering discipline, while also having breadth so that they are agile and adaptable for interdisciplinary innovation in a quickly changing technological and scientific landscape [13].

This article lays out a detailed initial road map for engineering schools and departments to drive quantum engineering education forward. The focus is on undergraduate quantum engineers and the recommendations are intended to be tailored for different academic contexts from teaching and undergraduate-focused four-year colleges and universities to research-intensive universities—there is no one-size-fits-all solution. In Section II, a brief description is provided of the technological, educational, and logistical context for quantum engineering, which also helps define the field. To facilitate quantum-awareness among budding engineers, in Section III, different pathways are presented to build a first course[1] in QISE accessible to any STEM major. To train quantum-proficient engineers, Section IV describes how to create a more complete undergraduate quantum engineering program. This includes QISE education research; a complete quantum engineering minor with three existing working examples; a quantum track within an engineering major with one current working example; and some remarks on a potential future quantum engineering major, which is believed to be premature at this stage. Then, Section V discusses how QISE presents an extraordinary opportunity to have a major impact on equity and inclusion in engineering as a whole, and provides specific recommendations to do so. Section VI walks through the most common quantum technologies and sketches hands-on training programs in each of them, which can be adapted to different academic environments. Finally, in Section VII, the recommendations are summarized.

The roadmap will also prove useful to other science departments creating their own QISE programs or partnering with engineering programs to do so. Additionally, a key recommendation of this article centers around an introductory "Quantum 101" course with minimal math content, like Anthropology 101 or Psychology 101, which the authors agree should be implemented at as many universities and colleges as possible to provide both an entry point to the field and a route toward promoting quantum awareness among the general population. Community colleges, especially, have returning older

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[1]A course is called a *module* in Europe, and refers typically in the U.S. to 48 h of instruction spaced out over 16 weeks in the semester system.

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students as well as many high school students taking classes, and including a general QISE course could have an outsize impact. Since a significant fraction of engineering students transfers from two-year colleges [14], this further justifies the design and wide-spread adoption of a "Quantum 101 course." Quantum 101 is included in Section IV as both broader impact and a recruiting tool for quantum engineering.

II. UNDERGRADUATE QUANTUM ENGINEERING IN CONTEXT

A. Technology, Industry, and Opportunity

The modern information age rests in large part on a foundation of semiconductor materials and devices that, at a fundamental level, require a quantum mechanical description. For example, semiconductor devices are the driving force behind modern computing, sensing, and networking technologies. In addition, an understanding of quantum mechanical band structure has led to the development of transistors, lasers, and photodetectors, which transmit and receive the glut of data carried by the Internet's fiber-optic backbone. Today, the continued miniaturization of semiconductor devices is approaching the end of Moore's law. As the transistor size standard approaches the semiconductor atomic lattice scale, quantum effects begin to limit rather than enable further progress. But, as has happened before in engineering, these limitations have spurred progress as one seeks to turn a bug into a feature, and develop new quantum-enhanced, rather than quantum-limited, technologies.

Quantum computers, whose nonclassical properties seem to evade the bounds of the extended Church-Turing hypothesis, could provide breakthrough capabilities in optimization [15] and machine learning [16], [17]. They also have the unrivaled ability to efficiently simulate quantum systems [18], [19] since they are quantum systems themselves, and thus, will find uses in chemistry, molecular biology, materials science, and drug discovery, to name a few applications. Quantum communication will enable quantum computers to be connected in a quantum Internet [20], [21], which will open up a host of possibilities, such as quantum secret sharing. Quantum sensing will open up new measurement modalities and sensitivities, such as quantum positioning systems (QPSs) capable of autonomous navigation (GPS-free) with accuracy down to the centimeter level.

Many of the predicted technology implications and corresponding investment can be traced back to quantum key distribution (QKD), which was proposed by Bennett and Brassard in 1984 [22]. This application allows two communicating parties to establish a secret key for secure communication in the presence of an all-powerful eavesdropper. QKD's potential importance was magnified enormously in 1994, when Peter Shor published a quantum-computer algorithm [23] for breaking the Rivest–Shamir–Adelman (RSA) public-key infrastructure on which Internet commerce currently depends. The possible vulnerability of RSA soon spurred research—both theoretical and experimental—in quantum communication and quantum computing that went far beyond QKD and algorithmic attacks on cryptographic protocols such as RSA.

Currently, one of the largest areas of activity in QISE is associated with quantum computers [24] and the creation of quantum networks [25]. There are already over 300 quantum simulators, or specialized "analog" quantum computers worldwide, built on over ten distinct physical architectures [19]. More general "digital" quantum computers already report achieving a quantum advantage [1], [24], [26], that is, meeting computational benchmarks not possible on a reasonable time scale with present classical computing resources. There is also ample activity related to the future of quantum sensing [27]–[30]. Quantum sensing has been applied in magnetometry [31] and ultraprecise clocks [32], among other areas. There may also be new untapped possibilities for improved classical information transmission using quantum communication [33]–[36]. Moreover, quantum communication and sensing principles have led to proposals for improving the angular resolution of astronomical imagers [37], [38] and the sensitivity of microwave radars [39]–[42], and additional such advances are anticipated.

Due to advances in QISE coupled to its potential scientific and societal impacts, quantum research has correspondingly expanded beyond academia and government laboratories into the industry. As of Fall 2019, there were already more than 87 quantum-related companies, spanning sensors, networking and communications, computing hardware, algorithms and applications, and facilitating technology, and this industry continues to expand [12]. The recent research by Fox *et al.* [12] pointed out that although researchers in this field are often Ph.D. physicists, as quantum industry products are moved out of development and into production, the need for engineers will increase. This work goes on to summarize the skill set valued by employers in the quantum industry: coding, statistical methods for data analysis, laboratory experience, electronics knowledge, problem solving, materials properties, and quantum algorithms. Inasmuch as nearly all quantum computation, communication, and sensing developments will involve a great deal of classical engineering, having some level of quantum awareness will be sufficient for many engineering graduates [43]. Examples include microwave engineers who will work on interconnections within superconducting quantum computers, photonics engineers who will work on the fiber links for quantum networks, and control engineers who will work on the various control systems required by quantum computing technologies. This quantum awareness could potentially be achieved with a single course or a two-semester sequence (see Sections III and IV-B), or with an undergraduate minor or track (see Sections IV-D and IV-E).

B. Quantum Education Landscape

The rapid growth of QISE as an academic discipline and viable career path for graduates has led to a growing number of formal quantum education efforts at all academic levels. Outreach efforts to a broad range of nonspecialist audiences have also been developed in limited contexts in recent years, and it is expected that education and outreach efforts will continue to expand. To supplement this article's emphasis on undergraduate quantum engineering education, the manner

in which undergraduate quantum engineering would fit into the wider quantum education landscape is discussed. This discussion focuses on the U.S. national landscape, and how those relationships, along with lessons learned in other activities, could inform the development of undergraduate quantum engineering programs and courses.

At the graduate level, a growing number of institutions have already launched or are developing master's degree programs, offering bachelor's degree holders in several STEM fields the specialized education and professional training to help them transition into the quantum workforce—or in some cases into Ph.D. programs in QISE. These programs face many challenges that undergraduate quantum engineering will also encounter, such as the need to accommodate a variety of incoming technical backgrounds and prior exposure levels to quantum science; the need to recruit and support a diverse student population in order to promote equity and a broad range of creative perspectives in the field as a whole; and the need to train teaching assistants and faculty from a wide range of departments to teach interdisciplinary QISE courses.

Outside higher education, numerous K-12 and public outreach programs in quantum information already exist or are under development, but the reach of such programs remains limited and the impact is relatively unknown. In an effort to begin establishing content frameworks for broadly introducing QISE into K-12 classrooms, museums, and other learning environments, an NSF-sponsored workshop in 2020 drafted a set of nine key concepts for future QIS learners [44] that can be adapted for engineering contexts. The National Q-12 Education Partnership and the Q2Work program are collaborating with teachers to expand these concepts for different ages and subjects and supporting the development of K-12 and public education initiatives [45]. To increase quantum literacy among educators and community stakeholders, and to develop curricula, the NSF supports teacher workshops that are piloting lesson design and implementation, as well as convergence accelerators QuSTEAM and the National Quantum Literacy Network [46]. Complementing these efforts are numerous summer camps, after-school programs, and online courses for students interested in QISE. These programs can provide inspiration and even a pipeline for students as they consider a future in quantum engineering [47].

K-12 formal quantum education is in its infancy and will require significant resources for full-scale implementation. This includes integrating quantum training into teacher professional development programs, researching and developing effective curricular models, and promoting long-term public awareness and engagement. Additionally, coordination with state and local education stakeholders is necessary for broad implementation.

As programs begin to scale up over the coming decades, they will begin to create a new population of students who enter college already primed with an interest in QISE and fuel the quantum information revolution, much as classical computer classes and opportunities fueled the classical information revolution starting in the 1980s.

The pressing need for quantum-proficient and quantum-aware engineers in the workforce, the growing set of graduate programs tailored to interests and ambitions in the field, and the expanding set of outreach and education opportunities for K-12 students currently leave a clear gap in the trajectories available to many quantum-interested students during their undergraduate years. It is essential that academia support and develop courses that address this gap at diverse types of institutions—including community colleges, undergraduate colleges, and large and small research intensive universities—and promote a wide range of pathways into the field.

For instance, because a large fraction of engineering students nationwide transfer from two-year colleges [48], community colleges and four-year institutions need to partner to remove barriers for students to make this transition in quantum engineering, just as in other STEM majors, tracks, and minors. To further support students as they move through their education, institutions could tie the development of quantum engineering programs to K-12 activities that connect with secondary school students and educators. Those having experience in K-12 and outreach programs have indicated that initial exposures should be varied to engage a broad range of potential future quantum engineers. For some students, quantum games [49] could be an excellent opportunity to pique interest, build intuition, motivate more future rigorous study, and even deepen understanding through repeated practice in different learning contexts. For others, examples of practical applications, interdisciplinarity, and societal impact embedded within courses could be more compelling. Professionals working in K-12 and outreach efforts indicate that demystifying the field rather than emphasizing its exotic attributes may lower the barrier for entry, and potentially attract a larger, more diverse student population, as students become aware that QISE is more than an intellectual exercise and offers both existing technological applications and stable and wide-ranging job opportunities. Future quantum engineering programs at the undergraduate level can perhaps improve retention by providing regular examples of existing career trajectories and facilitating mentoring relationships [50]. Anecdotal experience suggests that deliberate attention to these areas could be more critical in quantum engineering than in a more established field, where many students have career models available in the form of relatives and other community members.

Finally, a key component of QISE education is continuing education, called upskilling in the industrial context. As mentioned, a few universities already provide a master's program or graduate professional certificate in quantum engineering geared toward students with an existing undergraduate degree in STEM. Others offer online learning and certification for existing professionals. A growing number of online continuing education platforms, such as EdX, Coursera, etc., are offering formal quantum courses for the general public [51]–[53]. Informally, there have been a rapidly growing number of university courses placed on YouTube for public viewing. However, these programs and courses appear to be insufficient, or are too narrow in scope, to meet the rapidly increasing need for quantum proficiency across multiple disciplines. Given that the fields that contribute to QISE are not gender, racially, or ethnically diverse, upskilling programs are

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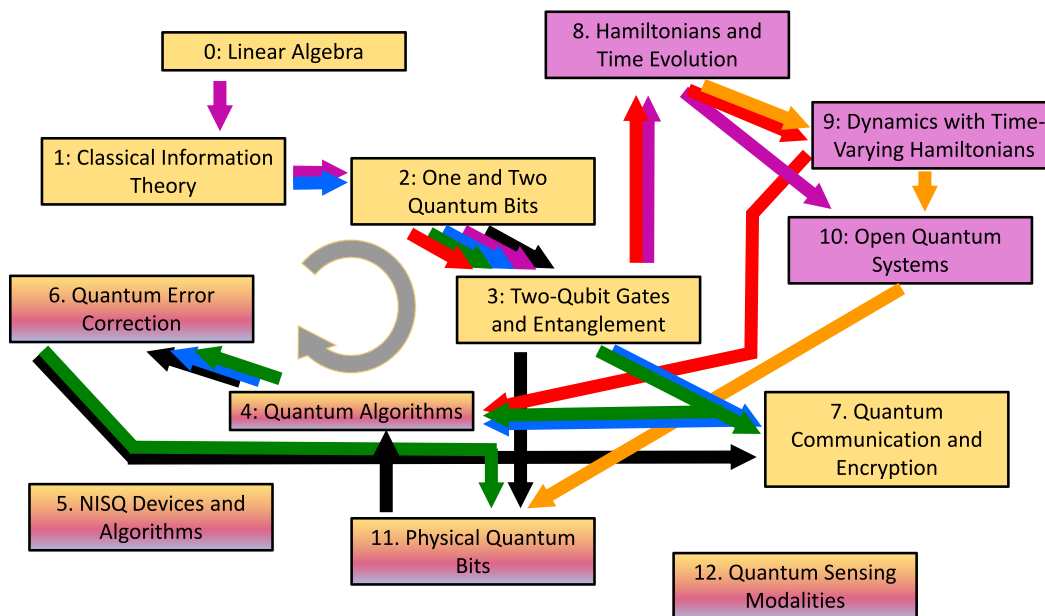ASFAW *et al.*: BUILDING QUANTUM ENGINEERING UNDERGRADUATE PROGRAM 5

Fig. 1. Quantum engineering course modules suggested for STEM students at any level (orange shaded text box), all levels plus advanced students (orange fade to purple), and advanced students only (purple). Arrows between boxes show different sequences taught by the authors (see text), which can be used as a basis for future engineering education research and course development upon formulating program and institution-tailored learning goals (green: Blais; purple: Carr; dark blue (first semester), orange (second semester): Economou; red: Kapit; and black: Lynn). The broad gray circular arrow highlights a particular choice (Girvin) as an example, 1-2-3-4-6. Note that particular connections, such as modules 2 to 3, are almost universal, while some, such as 5 and 12, are presently aspirational.

also unlikely to result in an increase in diversity across the technical workforce.

This all presents an opportunity for universities building their quantum engineering profile and programs. Introductory undergraduate courses such as those described in Sections III and IV-B can be leveraged as part of a university's MOOC program for existing workforce training. Over and above upskilling, currently the workforce needs [6], [7] are such that a large number of new BS/BE recipients will need to have quantum engineering education already in place. In the following sections, a plan is laid out for accomplishing this goal.

III. BUILDING FIRST QISE COURSE FOR STEM STUDENTS

Designing introductory courses in QISE is challenging because the field is in rapid technological flux and because courses are needed that are accessible to students from a wide variety of disciplines having varied mathematical and scientific preparation levels. In this sense, the challenge is similar to that faced by computer science in the early days. In addition, local faculty expertise varies at different colleges and universities. An introductory course might be designed for first year college students, graduate students, or anyone in between. As a result, the choice was made to present these recommendations for an introductory QISE course as a set of modules[2] from which a

course can be built and then tailored to meet the individual needs of the students, program, and faculty; some of these modules, such as the introduction to the gate model, can be made accessible to STEM students at any level (labeled with an E) below, whereas others such as quantum noise are likely more appropriate for advanced students (labeled with A). The full set is shown in Fig. 1.

This course is designed overall for engineering or at least STEM students as it has significant mathematical content. In Section IV-B, a separate Quantum 101 course, accessible to non-STEM students, is suggested. It is strongly recommended that a first QISE course as described in this section assumes only a background in high school and freshman[3] physics. In contrast, the Quantum 101 course in Section IV-B assumes no physics background at all. However, even for engineering students, one may want to avoid continuous variable systems in introductory courses, even unentangled, single-particle ones. Studying them in depth typically requires quite a lot of prerequisite specialized mathematical knowledge, although some QISE educators have explored other approaches [54]. Some studies suggest the discrete-variable or "spin-first" approach to quantum mechanics provides more opportunities for students to understand the underlying concepts independently from the complex mathematical calculations often associated with quantum mechanics [55]. Appropriate to a college-level class, it is assumed students will have taken a linear algebra course beforehand, and recommend spending the first week on review of the basics of linear algebra as a refresher. Alternatively, one could choose not to rely on linear algebra as a prerequisite and teach the required concepts as part of

[2]Modules may be called *components* in Europe, and refer in the U.S. to sections or units from which a course is constructed. Modules typically last more than one lecture but much less than the length of a course, and commonly, take one to four weeks. Thus, in a 16-week course, there may be about four to ten modules.

[3]Freshman refers to the first year of college, called Y1 in Europe.

the course (at the expense of covering less ground in QISE)—see Section III-A. Each module is envisioned as taking one to three weeks of a standard semester course, depending on depth and the educational level of the students.

The goal of this recommendation is to be able to easily combine modules to create an introductory course at any level based on the goals of the program. To use a few of the authors of this article as examples, Blais taught an advanced course aimed at preparing seniors and graduate students for further specialized courses and research, which proceeded with the sequence 2-3-7-4-6-11; Carr has taught quantum mathematical fundamentals as 0-1-2-3-8-10; Economou teaches two courses, one purely on quantum software, roughly following 1-2-3-7-4-6, and one focused on physical platforms and their control, following 8-9-10-11; Girvin has taught an introductory quantum computing course aimed at first-year students onward that roughly followed the sequence of modules 1-2-3-4-6; Kapit taught similar level students as Blais with 2-3-8-9-10-4; and Lynn has taught an introductory course aimed at sophomores[4] onward but sometimes taken by first-year students and even advanced high-school students, which followed the rough sequence 2-3-11-4-6-7, interspersing ideas from 1. Carr has used module 0 as an add-on to a variety of STEM classes with quantum content when students have little to no knowledge of linear algebra. The choice of modules would also be informed by the selection of more advanced courses the program offers beyond this introduction. For example, a program that offers a dedicated quantum algorithms class might deemphasize much of module 4 in the introductory course, and a program that offers microwave engineering courses would certainly want to include module 9. Such a course could be titled, "Introduction to Quantum Engineering."

Comprehensive learning goals may vary somewhat from course to course and should be set for any implementation of the modules. The key concepts for future QIS learners [44] presents a set of essential QISE ideas, but learning goals based on this must be developed. It is an open engineering education research question as to what learning goals would be appropriate in the context of undergraduate quantum information engineering. Finally, note that although a survey of prequantum information era quantum mechanics, sometimes called "Quantum 1.0", is not included explicitly in the modules, it is implied in many of the topics as an appropriate background to "Quantum 2.0", i.e., QISE. Alternately, Quantum 1.0 can be included as a separate module on extant pre-QISE technologies, such as lasers, MRIs, atomic clocks for navigation, the photoelectric effect in motion sensors, etc., for example, as a nonmathematical Module 0 in place of linear algebra.

The modules below and other course recommendations are focused more on quantum computing, with less content covering quantum communication and quantum sensing. The development of additional modules is supported and encouraged in these critical QISE pillars, which will be essential for providing a complete curriculum.

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[4]Sophomore refers to the second year of college in the U.S., Y2 in Europe.

A. Module 0: Linear Algebra for QISE (E)

Vector spaces (superposition, concept of a basis), linear transformations, matrix multiplication, noncommutativity, diagonalization, inversion, Hermitian and unitary operators, trace and partial trace, outer and tensor products, scaling up to larger matrices numerically. These concepts can be introduced in the context of the single qubit, i.e., 2×2 matrices, and their tensor products. As linear algebra is a strong prerequisite for most QISE, students can either take it as a separate course or it can be included here as a focused unit. The alternate option is a nonmathematical quantum concepts course as in Section IV-B.

B. Module 1: Classical Information Theory (E)

Basics of bits, gates, communication, randomness and statistics, error correction, parity and data compression. It discusses the basics of computation itself, shows that the number of distinct programs mapping n input bits to m output bits is doubly exponential $N = 2^{m2^n}$, and introduces the notion of a universal classical gate set that can reproduce any of this enormous number of programs. Vector spaces could be introduced at this point, as in Mermin's book [56], where classical bits are represented as vectors and gates as matrices. This eases the transition to qubits.

C. Module 2: One and Two Quantum Bits (E)

Quantum bits, superposition states, measurements and the Born rule. Single-qubit Hilbert space: linear operators, Dirac notation, orthonormal bases and basis changes, qubit rotations, and the Bloch sphere. Expectation values and variance of measurement results. This introduces students to the basics of quantum theory in the concrete context of the analytically solvable problem of 1 or 2 qubits. It helps students understand multiqubit Hilbert space and operators, leading to tensor product spaces and the combinatorial complexity explosion.

D. Module 3: Two-Qubit Gates and Entanglement (E)

The CNOT gate and the circuit model of computation. Bell states and nonclassical correlations. A typical example would be the spin singlet or Bell states, in which information is encoded in the global system while no information is contained in the constituent qubits. Quantum dense coding and monogamy of entanglement. The no-cloning theorem and state teleportation. Universal quantum gate sets. This shows students how to build quantum computation from basic elements (gates) and some of the surprising outcomes. Depending on the programmatic emphasis, this module could focus on entanglement more generally, for instance, in single-ion optical atomic clocks, cold molecular ion spectroscopy, quantum communications, random key generation, etc.

E. Module 4: Quantum Algorithms (E/A)

Early examples of quantum advantage in computation: the Deutsch, Deutsch-Jozsa, Bernstein-Vazirani, Simon's algorithms. Phase kick back from controlled unitaries. Oracle algorithms. Grover's algorithm, phase estimation, and the

quantum Fourier transform. In discussing Shor's algorithm, one may want to focus on the QFT and the period-finding algorithm more than factoring itself, since the factoring application depends on number theoretic results, which are less relevant to quantum algorithms more broadly. Students will gain an understanding of the breadth of quantum algorithm development.

F. Module 5: NISQ Devices and Algorithms (E/A)

Noisy intermediate scale quantum devices. Heuristic algorithms, including the Variational Quantum Eigensolver (VQE), the quantum approximate optimization algorithm (QAOA), and possibly machine learning algorithms. Error mitigation. Use of online software and cloud-accessible hardware. Students will understand how to program actual quantum hardware and learn some minimal quantum software skills.

G. Module 6: Quantum Error Correction (E/A)

Error models: coherent errors, incoherent errors as coherent errors in a larger Hilbert space, correlated errors. Repetition code for dephasing or bit-flip errors. Shor code. Concatenation, code capacity threshold versus fault-tolerance threshold. Quantum computers are analog and errors are continuous, but *measured* errors are discrete. Error correction is one of the most essential topics in QISE and students need a careful introduction to clarify the contrast with much easier error correction methods on classical computers.

H. Module 7: Quantum Communication and Encryption (E)

Inability to perfectly distinguish nonorthogonal states and no-cloning theorem. The BB84 QKD protocol. Entanglement-based QKD protocol (E91). Entanglement swapping and quantum repeater networks. Error correction in communication and entanglement distillation. This module can build on module 3, and is the intro to the power of QISE for communications.

I. Module 8: Hamiltonians and Time Evolution (A)

Eigenstates and eigenenergies of a Hamiltonian. The Schrödinger equation and time evolution. Expectation values; motion and transitions as interference phenomena. The harmonic oscillator and general N-level systems. Basic properties of systems with multiple identical particles. This module is especially useful for building a knowledge of quantum and classical control systems, since quantum gates are based on the underlying dynamics.

J. Module 9: Dynamics With Time-Varying Hamiltonians (A)

Dynamics and control of two-level systems subject to AC fields. Quantum mechanics in a rotating frame, and the rotating wave approximation. Rabi oscillations. Control of harmonic systems with an auxiliary anharmonic element. The quantum adiabatic theorem. This module naturally builds on module 8, or can be expanded and substituted in place of it. AC fields such as microwaves are key to classical control of quantum systems.

K. Module 10: Open Quantum Systems (A)

The density matrix formulation of quantum mechanics. Entangling and nonentangling noise. Fermi's Golden Rule. Models for a bath. Reduced density matrices. Physical noise mechanisms. Quantifying coherence through estimates of relaxation and dephasing times. An essential concept in QISE is the fragility of quantum states. This module can provide underlying knowledge to comprehend the severity of the decoherence problem.

L. Module 11: Physical Quantum Bits (E/A)

Broad overview of candidate systems for quantum computing. Superconducting qubits, trapped ions, spin qubits. At a more advanced level, one can also present photonic systems, neutral atoms, and topological qubits. One could also formulate this module as a more in-depth exploration of a single class of qubits.

M. Module 12: Quantum Sensing Modalities (E/A)

Quantum-enhanced resolution in optical interferometry: classical operation versus N00N-state (entangled) operation. Heisenberg uncertainty principle for the quantum harmonic oscillator: coherent states and squeezed states. This will demonstrate to students the basic principles of quantum-enhanced accuracy in optical interferometry, including coherent-state operation with standard-quantum-limit scaling versus squeezed-state operation with Heisenberg scaling.

IV. CREATING COMPLETE UNDERGRADUATE QUANTUM ENGINEERING PROGRAM

The purpose of this section is to identify the issues associated with quantum engineering program development and to outline possible approaches that can be tailored to individual institutions, including course development and a minor or track. In addition to resource constraints and opportunities particular to each educational institution, it is useful to keep in mind the needs of the QISE industry as it stands today and in the near future. This is shown in Fig. 2. Higher levels of specialization are at the top, while lower levels of specialization, but also more jobs, are at the bottom. Positions near the very top are most likely to be filled by Ph.D. graduates, while MS graduates will be at the middle and lower levels, and BS/BE graduates will form the base. Undergraduate program development must concern itself with filling all three of these niches. The following discussion covers STEM education research in QISE, developing concepts-focused and advanced undergraduate courses, and practical plans for minors and tracks, closing the section with a few comments on a future quantum engineering major.

A. QISE Education Research

There are several pedagogical challenges associated with developing a quantum engineering program. One must contemplate the content of individual courses and degree programs. One must also bridge the gap between what the faculty think they are teaching and what students are actually learning.
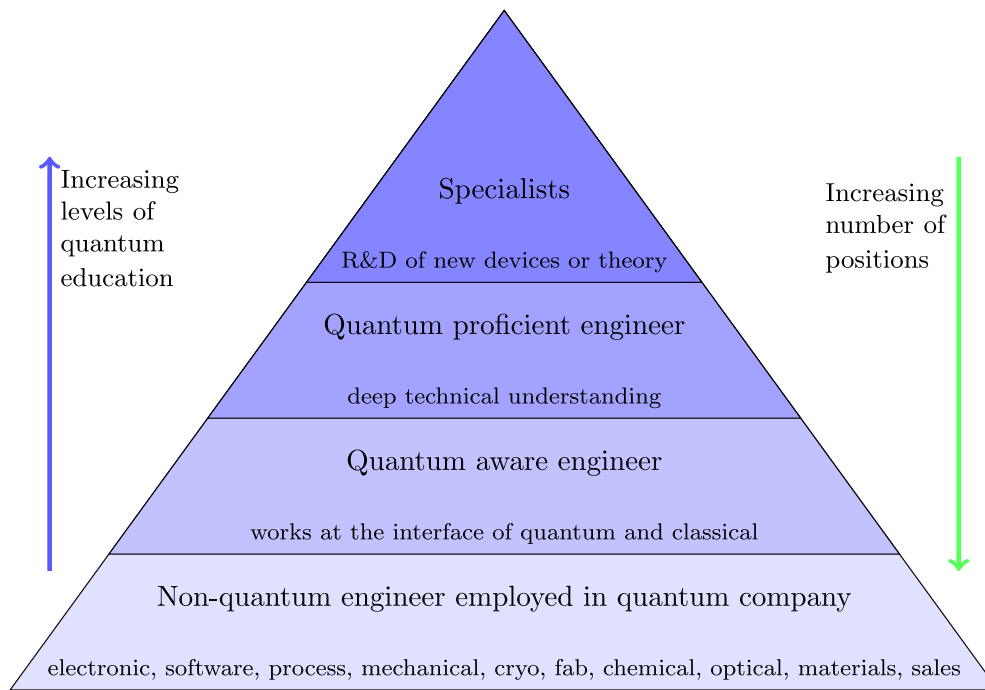
Fig. 2. Representation of the relative number of anticipated positions for various sectors of the quantum job market and the requisite level of quantum education for each.

Methods to do so include evidence-based active-engagement pedagogies and curricula. This bridge should ideally be research validated in the context of STEM education, as well as be effective for students from diverse backgrounds and prior preparations. The interdisciplinary nature of QISE education implies that the diversity in students' prior preparation and background is likely to be greater in QISE-focused courses. This fact makes it even more critical to use STEM education research-validated curricula and pedagogies that focus on helping all students, not just the best prepared, to learn. As the quantum engineering education roadmap contained in this article develops new programs and courses from scratch, one has the unusual opportunity to do things well from the ground up, rather than improving existing courses as, e.g., in quantum physics education research [57]–[64].

Development and implementation of these types of pedagogies and curricula entail thinking carefully about the learning objectives and goals of each course and aligning these with instructional design and assessment (e.g., is a pen and paper exam able to assess students' proficiency in aligning an optical system?) It also entails having a good understanding of students' prior knowledge and skills that can be built on, the common difficulties students have after traditional lecture-based instruction [65], [66], and consideration of how to leverage the diverse prior preparation of students effectively. For example, education research has studied students working in small groups on collaborative group problem solving, tutorials, and clicker questions [61], [67]–[75] using approaches in which individual accountability has been integrated with positive interdependence, e.g., through grade incentives. These methods have been shown to improve learning outcomes for all students. Furthermore, it is critical to contemplate how different courses build on each other in a degree program in order

to maximize their benefit for students who take those courses simultaneously or sequentially.

Explicit effort should be made to ensure an equitable and inclusive learning environment, as discussed in Section V, so that students from diverse demographics and backgrounds have an opportunity to excel. Moreover, validated assessment tools need to be designed to measure growth in students' knowledge and skills, as well as development in their motivational beliefs about quantum. Assessing and improving the motivational beliefs of students from different demographic groups about QISE (e.g., their QISE-related self-efficacy or sense of belonging in classes) are especially important to ensure that students from underrepresented groups also have high self-efficacy and sense of belonging, since these beliefs can impact student outcomes, as well as their short and long-term retention within the field. Along with issues of diversity, equity, and inclusion, consideration of social, societal, ethical, and sustainability issues of QISE would be beneficial, in line with directions in engineering education worldwide [76]–[78].

Finally, although there has been some education research on the effectiveness of QISE courses, more needs to be done as new programs are developed. This research needs to examine not just theory courses but also hands-on experimental experiences and lab courses, as many of the desired skills are best learned in these environments [79]. Hands-on learning is covered in Section VI.

B. Freshman-Level Concepts-Focused QISE Courses: Quantum 101

Many in the community assert that offering QISE courses at the freshman or sophomore level, without necessarily requiring linear algebra, is desirable in order to stimulate students'
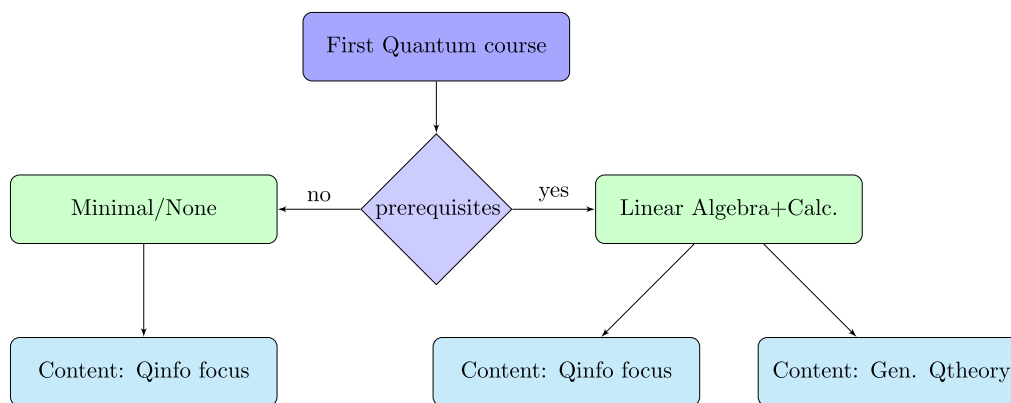
Fig. 3. Several possibilities exist for first quantum courses for students outside physics departments. The fundamental decision is whether prerequisites are required or not. The general consensus in the community is without prerequisites the course should be focused on quantum information topics, labeled here as "Qinfo focus." For areas of engineering that require a quantum education, departments have a decision to make. The first option is to have students take a specialized quantum information course, resulting in quantum-aware engineers. The second option is to give students a holistic quantum education, which will better prepare students for more advanced quantum courses and applications of the quantum theory encountered in industrial settings, resulting in quantum proficient engineers—see also Fig. 2.

interest through concepts and applications, and to help resolve structural inequities in STEM pedagogy and improve diversity (see, e.g., Fig. 3). For instance, such a course can be offered in community college and military school settings, and as a "Quantum 101" option for students who have a general interest in learning the quantum information perspective. Depending on the setting, the modules above would need adjustment or supplementation to effectively provide an entry point into QISE.

By learning concepts and applications first, without the need for advanced mathematical formalism, students may gain appreciation for the topic and intuition for the connections between concepts and applications. Moreover, avoiding advanced mathematical prerequisites or co-requisites lowers the barrier to entry for students who come to the field with less mathematical preparation, or relatively late in their education. A similar approach is common in computer science and math departments, where programming concepts, or proof concepts courses, are often required entry points for a major or minor. Such courses also function as recruiting tools due to their wide accessibility.

This approach, in addition, allows the connection between end-use applications and discussion of potential career pathways, which may appeal to technology-oriented students. Therefore, such courses may broaden the on-ramp for quantum engineers and help to recruit and retain a more diverse, more equitable, and more inclusive cohort of students into the discipline.

A potential concern with a QISE course that does not require sophisticated math is that it would require sacrificing rigor or accuracy. Surprisingly, that does not have to be the case, and there now exists a formalism that can explain quantum states, the concept of superposition, entanglement, and unitary transformations, as well as quantum algorithms rigorously without the need for linear algebra [51], [52], [80]–[82]. The only requirement is knowledge of basic arithmetic. Through this method, which some of us have used for outreach to high school students, in courses at the freshman level, and for courses drawing broadly on all STEM students with no

quantum background, students can predict the outcome of quantum circuits. This is a nice complement to using online cloud processors or simulators, especially the drag-and-drop option that IBM offers to build circuits (which does not require text-based programming skills), as they can verify the results of their calculations using the online interface [82]. At this time, more research is needed to understand these approaches and their overall efficacy as courses and as bridges into more advanced material.

Finding space for such a concepts course in an engineering degree is a difficult task, but one that may be an essential entry point to the field at many institutions. In programs where linear algebra is not a significant barrier for the student body, a first course as described in Section III can provide an efficient grounding in the concepts of quantum information, couched in the same mathematical language typically used within the field. A one-semester introduction at this level enables students to engage with a variety of further literature and instructional resources available in the field, and can even provide enough quantum awareness to prepare engineering graduates for entry-level employment in the quantum industry. In contrast, students in many programs do find linear algebra to be a significant barrier to enrollment in a first quantum course. In that case, a QIS concepts course can give students a solid understanding of the fundamental concepts and applications, as well as the motivation to pursue further studies. Students who go on may then need to take more courses overall to arrive at a given level of literacy in the field, but this tradeoff can be more than worthwhile in exposing more students to the possibilities of QISE.

There are three major institutional uses for this kind of course. First, it can be taught in community colleges, military schools, and universities that do not have the resources to create a more advanced QISE curriculum, let alone QISE degrees, to provide quantum awareness to their students. Second, it is valuable to universities that do not yet have advanced QISE courses and degrees, as a stepping stone toward building quantum engineering programs. Third, it can ease entry into more

advanced and demanding courses, and provide intuition into QISE concepts without conflating them with the mathematical formalism itself.

C. Considerations in Creating QISE Courses

To develop a robust quantum workforce, it is necessary to educate students about more than simply qubit modalities, quantum circuits, and quantum algorithms. For example, many nascent offerings at universities lack education in quantum sensing, quantum communications, the theory of quantum hardware, and lab courses on quantum hardware. Rather, the majority of offerings presently focus on quantum information and quantum algorithms. Yet, this does not at all reflect the breadth of needs in industry or academia [12]. Indeed, the primary difficulty in quantum hardware and quantum technologies (sensing, communications, and computing) is understanding the hardware itself, which is also changing. For example, while developing commercial quantum algorithms is one of the grand challenges of the coming decade, building quantum computers that can run these algorithms reliably at scale is equally important. Additionally, developing interconnects for quantum networks of either sensors or devices remains a challenge. As such, within a majority of vertically integrated quantum companies, the quantum algorithms team is but a fraction of the total headcount and likely composed of Ph.D.-level employees for the foreseeable future. Thus, overemphasizing algorithms at the expense of hardware at the undergraduate level will likely miss many employment opportunities.

In contrast, the quantum engineer requires a broad knowledge of different technologies, including atoms and ions, semiconductors, superconductors, integrated optics, as well as microwave and RF control and readout [2]–[5]. At the same time, the quantum engineer can pursue different areas of specialization, including communications, cryptography, and information theory; quantum computation and classical control systems; and quantum sensing and devices. Undergraduate QISE education to date remains almost entirely housed in physics departments focused on fundamental science in preparation for the physics Ph.D. Thus, a strong advantage of a quantum engineering program is to create BS/BE level students with a general knowledge of quantum technologies and specializations. Advanced undergraduate quantum engineering programs should seek to capitalize on this opportunity at all levels by integrating many technologies and specializations either into separate topical courses, where resources are available, or into broad survey courses. Ideally, any quantum engineering program would offer the opportunity to learn quantum communications and cryptography, quantum sensing and devices, and quantum simulations and computing.

College and university administrations considering augmenting existing engineering programs with a minor or a track may offer two concerns: 1) satisfying the Accreditation Board for Engineering and Technology (ABET) and 2) the constraints of course creation given finite resources. To address the first concern, ABET engineering criteria give programs considerable flexibility in attaining student outcomes and other requirements. In fact, the revised ABET engineering criteria and continuing efforts to further incorporate diversity, equity, and inclusion in the criteria [83] are well aligned with the educational program goals of this article. QISE courses can easily be designed to meet specific ABET criteria, such as: 1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics and 2) an ability to apply engineering design to produce solutions that meet specified needs with the consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. To address the second administrative concern, for example, a "Digital Signal Processing" track versus a "Microwave Engineering" track may differ in practice by only three or four courses. That leaves essentially three to four available "slots" to make a minor or a track. Thus, it is paramount that quantum engineering programs integrate closely with existing engineering programs, as will be laid out in detail in Sections IV-D and IV-E.

Another issue of concern, and also a major opportunity, is the lack of textbooks suitable for quantum engineering. Quantum theory textbooks are predominately written by physicists and assume a great deal of physics background, such as Hamiltonian and Lagrangian mechanics, thermodynamics and statistical physics, etc. While there are some exceptions [84]–[86], there is a need for quantum theory textbooks for nonphysics majors that provide education in general aspects of quantum theory. Even more seriously, to the best of our knowledge, no quantum engineering textbook presently exists for learning the diversity of quantum hardware at the advanced undergraduate level—see the detailed descriptions in Section VI. Introductory and review articles exist at a wide spectrum of levels from graduate to professional QISE researchers [2]–[5], and there are even a few graduate-level textbooks with hardware components, such as [87]. However, much of this material is too specialized or advanced for undergraduate courses. Moreover, in some cases, the state of the art is changing on a rapid time scale, which presents another challenge in course design and also places a burden on instructor capacity. For specific topics, there are some excellent materials aimed at undergraduates, e.g., for superconducting devices [88]. To create a holistic hardware course, the instructor is forced to cobble such materials together. Similar issues arise for quantum sensing and quantum characterization, verification, and validation. The latter is particularly problematic, as a major task for a quantum engineer at the moment is to assess the performance of quantum hardware and improve designs or control strategies based on this assessment. Broadly integrating classical engineering expertise in, e.g., control theory into the quantum domain, i.e., *quantum* control theory, will likely occur over many years.

D. Quantum Engineering Minor

A quantum engineering interdepartmental minor is advantageous because it supplements and leverages existing degree programs in engineering, computer science, mathematics, and the fundamental sciences. Although minors can be highly

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variable from institution to institution, a typical minor requires six to seven courses: three are considered core to the minor, and the remaining courses are electives. The electives may be chosen from relevant subjects within the department hosting the minor, from other departments (assuming prerequisites requirements are met), or from a student's home department. This has two consequences. First, it opens more pathways for nontraditional students to study quantum technology. Second, it avoids overloading students with subjects outside their college. The primary decision for the host department(s) is to determine which QISE subjects should constitute the three core courses and in which departments they are taught. Such considerations are usually particular to each academic institution, but obvious candidates are electrical engineering, computer science, materials engineering, chemistry, and physics.

There are a few quantum engineering minor programs in the U.S. with many more to appear shortly. Provided as examples here are the quantum engineering minors at the Colorado School of Mines, at the University of Colorado Boulder, and at The Virginia Polytechnic Institute and State University (Virginia Tech), which offer an initial roadmap for creating a minor at public research universities.

These are intended as working examples, and should not be construed as the only or the best programs out there. Different institutions may structure their degrees differently and may emphasize quantum computing, communications, or sensing, depending on the expertise and interests of the local QISE faculty; likewise different hardware platforms may be emphasized depending on available resources. To help ameliorate the latter, programs are recommended to partner with national labs and nearby institutions, when possible, as well as incorporate internships in industry to maximize breadth of experience in new quantum engineers.

The Colorado School of Mines quantum engineering minor requires six courses as part of the Quantum Engineering Interdisciplinary Academic Program supported by six departments, including electrical and materials engineering. The first four are linear algebra, and three of the following courses: 1) fundamentals of quantum information; 2) quantum programming; 3) low temperature microwave measurement; 4) quantum many-body physics; and 5) microelectronics processing. Students can either take their remaining two courses from this list to round out their quantum education, or else any two from the quantum engineering course catalog to increase specialization. The catalog is extensive, but includes existing STEM courses, such as feedback control systems, digital signal processing, semiconductor device physics and design, computational materials, and machine learning. This minor required the creation of four new courses targeted at quantum engineers, namely, 1)–4). Course 1) is covered in Section III, while 2)–4) were designed with the considerations of Section IV-C in mind. Because Mines is a purely STEM school, many prerequisites are not necessary to specify.

The University of Colorado Boulder quantum engineering minor requires six courses with three prerequisites: 1) programming; 2) calculus; and 3) linear algebra. Students are then required to take the following three courses: 1) foundations of quantum engineering; 2) foundations of quantum hardware; and 3) introduction to quantum computing for the theory track, or quantum engineering lab for the experimental track. Flexibility is built into requirement 1): two semesters of upper division quantum mechanics in the physics department can also satisfy the requirement. The remaining three courses are required from a large elective list, which, similar to Mines, is drawn from existing STEM courses across campus, such as microwave and RF laboratory, control systems analysis, machine learning, and solid state physics. Thus, similar to Mines, the quantum engineering minor required the creation of four new courses, some of which had already been taught in pilot form as a proof of principle.

The Virginia Tech QISE minor is a joint effort among seven departments/programs across the College of Science and the College of Engineering, and it requires eight courses. Five of them are mandatory: linear algebra, an introductory (freshman/sophomore level) QISE course without any prerequisites (see Section IV-B), an advanced QISE course with only a linear algebra prerequisite (modules 1–4, 6, and 7) described in Section III, and two programming courses that include classical programming (e.g., Python), quantum programming (using online hardware and quantum languages such as Qiskit), and use of collaborative software. The sixth course is a choice between one focusing on physical quantum platforms (an expanded version of modules 9–11 in Section III) and a more advanced theoretical quantum computing course. This allows students from diverse departments to deepen their QISE knowledge irrespective of whether they have a quantum mechanics background. The remaining two courses are selected out of a long list of existing electives from six departments. The creation of this minor required three new courses (the introductory QISE course and the two programming courses).

Thus, creating a quantum engineering minor in a STEM environment can require the addition of three or four new courses, some of which may only need adaptation from preexisting instruction. The largest barrier to the minor is hands-on training on quantum hardware, which is treated separately in Section VI. These examples should not be taken as an exact or detailed plan but instead as first successful attempts that can be improved upon. It is more important to teach engineering principles and design in the context of QISE than to focus on any particular quantum technology or platform, as also reflected in the diverse technologies found in Section VI. This is critical for providing the depth of education and agility necessary to support student success in future careers, whether or not they are quantum related.

E. Quantum Engineering Track Within Engineering Majors

A quantum engineering track within an existing engineering program is an alternative option to the minor. In the near term, it provides a means to more readily design a program without the need for interdepartmental collaboration. Existing engineering programs already have many subjects that are relevant to quantum engineering. Thus, a track should not be difficult to construct within such an existing framework. Each engineering

department would be able to offer multiple customized tracks comprising a series of courses that enables students to obtain domain-specific knowledge through both "classical" and targeted quantum subjects. For example, an electrical engineering or computer science department could offer a quantum software track, an algorithms track, a quantum hardware track, etc. When paired with the core courses the students have chosen to form their degree program, the track provides a supplemental, in-depth training in topics relevant to a future quantum workforce, such as low-level control of quantum hardware, quantum programming languages and paradigms, quantum compilers, and the like, while fundamentally retaining the structure of their bachelors degree.

A typical quantum engineering track in an engineering program could involve the standard engineering courses plus a two-semester sequence of quantum engineering I-II, two semesters of hands-on training on quantum hardware I-II, and two specialty courses drawn from a list of standard courses available at the university, such as nanofabrication, materials science, solid state devices, machine learning, etc. For a more software-centric track implementation or option quantum computation and algorithms can take the place of quantum hardware II. The quantum engineering I-II sequence should cover material from Section III and indeed may draw directly on such a course designed for the minor in Section IV-D. Depending on the engineering discipline, additional requirements may be necessary. For example, at the University of Chicago, there is a quantum engineering track in molecular engineering, which also requires intermediate electromagnetism, a necessary component for classical control systems.

The authors believe it would be a good idea to add to a quantum engineering track along these lines a first year freshman-level concepts-focused course, Quantum 101. Such a course is also a highly useful addition and recruiting tool (see Section IV-B). Likewise, instrumentation or lab courses offering opportunities for the quantum engineer to develop experience on two or more technologies is an important consideration (see Section VI).

F. Future Quantum Engineering Major

The minor or track may be part of existing engineering departments, or be part of an interdisciplinary program supported by several departments, including electrical engineering, materials engineering, engineering physics, computer science, chemistry, and applied mathematics, to name one of many examples discussed here. Such quantum engineering programs may naturally evolve to the point of seeking a complete undergraduate degree titled "quantum engineering." Programs can in some cases lead to stand-alone departments, as one observes in the past with nanoengineering and other engineering specializations.

Whether in a program or department, the development of a quantum engineering major is a complex undertaking that may not yet be suitable for the majority of academic institutions. It is foreseeable that such majors may more commonly emerge as quantum technologies mature over the next decade and quantum engineering develops as an engineering discipline. The

current ambiguity of a quantum engineering major and what it entails could adversely impact the employment prospects of students graduating with such a quantum engineering degree. For example, employers would be understandably uncertain about the preparation and training of a quantum engineer. On the other hand, a track record of hires that were electrical engineers or software engineers, now with a minor or a track in quantum engineering, may make evaluating such a candidate relatively straightforward.

V. Promoting Diversity in Quantum Engineering Undergraduate Programs

Advances in QISE and the development of associated technologies rely on expertise from multiple disciplines, including, but not limited to, applied mathematics, chemistry, computer science, electrical engineering, material science and materials engineering, and physics. These disciplines have historically struggled to be inclusive and equitable, as reflected in persistently low numbers of graduates identifying as coming from educationally marginalized racial and ethnic groups, sexual preferences, and genders, including women, the largest marginalized group of all. For example, in the U.S., the overall percentage of bachelors degrees in physics awarded to women (20%), Hispanic students (9%), and African American students (4%) has remained stubbornly low for decades [89], with similar trends in the other fields. Not surprisingly, the existing quantum workforce in industry is correspondingly lacking in diversity. The issues of each discipline with respect to broadening participation and facilitating success of marginalized students (e.g., for physics [50]) compound to paint a bleak picture for building diverse, equitable, and inclusive quantum engineering undergraduate programs going forward.

It is therefore imperative that curriculum designers, researchers, and university administrators implementing QISE programs think critically about issues of diversity, equity, and inclusion from the beginning. While the field and the associated undergraduate academic programs are in the early stages, one has an opportunity to effect long-lasting change in QISE and its related disciplines, and offer equitable outcomes for students from all backgrounds. Moreover, a large percentage of engineering students in the U.S. are foreign born. A careful exploration of barriers to learning for foreign born students will be helpful toward producing the best quantum engineers. Some of these barriers interface with diversity, equity, and inclusion issues. The authors recognize that there is not a one-size-fits all solution and that education programs must be tailored to different institutions, departments, and disciplines.

A. Recommendations for Course and Program Design

Here, some recommendations are provided for any institution looking to add more QISE content to their curriculum in a way that also intentionally promotes diversity, equity, and inclusion. This is a world-wide issue, but the focus of this and following sections of Section V is on the U.S. context, needs, and initiatives.

All courses and curricula should have learning outcomes for required QISE knowledge and skills [61], [67]–[73]. Courses

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should *also* have explicit outcomes to promote a high sense of belonging, self-efficacy, and identity as a person who can excel in QISE for all students, but particularly students from historically marginalized groups, e.g., women and racial/ethnic minorities [90]. Self-efficacy, or belief in one's ability generally, is known to be a key predictor of success in STEM fields [91]–[93]. Outcomes can be evaluated through entry and exit surveys of students in each introductory QISE class. For example, in an introductory quantum mechanics class, student self-efficacy in performing quantum calculations and understanding quantum concepts should increase by the end of the course. In order to achieve these learning outcomes, it is critical for faculty to ensure that the learning environment in their courses and labs is equitable and inclusive. To this end, faculty need to be trained in inclusive mentoring approaches, such as being genuinely invested in the success of the student and having a growth mindset about their student's potential to excel [94]–[97]. There is also evidence that brief interventions in the classroom at the beginning of the term can make the learning environment more equitable and inclusive [98], which can have long-term effects on the success of students from marginalized groups [99]–[101].

Evaluation of new courses and degree programs should include key elements related to diversity, and be coupled to larger longitudinal studies of climate, culture, and industry hiring (for example, this could be included in continuing industry surveys carried out by the Quantum Economic Development Consortium). In all data gathering efforts, it is critical to disaggregate quantitative data about student outcomes by race/ethnicity and gender. Additionally, qualitative interviews are the key to understand the impact of curricular and mentoring changes on students' experiences and persistence to degree. The recruitment of more marginalized students is not enough to achieve a truly diverse program and workforce; rather, the key metric of progress should be these students thriving in the program as well as their degree attainment and subsequent employment. In other words, *equity of outcomes* is a key metric of success for any program.

One concrete recommendation for increasing diversity is to restructure science and engineering programs to accommodate QISE knowledge earlier in the curriculum. Departments should prioritize creation of a single "quantum awareness" introductory course as a short-term goal (see Section IV-B). This is critical for institutions that are not able to implement a full QISE program. Early introduction of QISE content, the field's impact, and future career opportunities are especially important for retaining students from economically disadvantaged backgrounds (who are often also marginalized students) because it enables them to see viable career paths to well paying jobs in the quantum industry. In addition, professional development skills should be integrated into the curriculum early to facilitate student confidence. Students may also benefit from targeted training on how to work in diverse teams [95].

Another way to incorporate knowledge of real-world QISE applications early on is through undergraduate research experiences. Perhaps more than any other intervention, undergraduate research has been shown to increase student self-efficacy

and persistence to degree, both in the general student population [91], [102] and for marginalized students in particular [92]. There is also evidence that undergraduate research experiences can encourage marginalized students to pursue higher education after their undergraduate degree, which would help to diversify the existing Ph.D. pipeline [103]. Undergraduate research experiences can be offered in a variety of ways; for example, research could be completed at the student's home institution or in partnership with more well-resourced institutions in the area (for example, through summer programs). However, it must also be stated that not all undergraduate research experiences are equal in quality and effectiveness. High-quality mentoring is essential to achieving increased self-efficacy among students. Mentors need to be prepared to provide advice not only on research but on other professional skills, such as time management and scientific communication [92]. Increasing social support for undergraduate researchers through designated cohorts can help them build community with their peers and see themselves as engineers and scientists, something that is often difficult for marginalized students who do not see themselves reflected in the celebrated leaders of the field. Finally, there is some evidence that longer research experiences can be better for students, because they are able to form a stronger relationship with their mentor and other students [103]. To that end, it is recommended that departments seriously consider implementing multiyear research programs for undergraduates during the academic year, if possible. Smaller institutions might pursue partnerships with research groups in the industry or at nearby academic institutions to facilitate longer-term undergraduate research experiences. It is also important to note that there are significant barriers for many students to participate in undergraduate research, which can be magnified for many students from marginalized groups. These barriers include not having the ability to participate during the summer due to financial or family reasons. Thus, when developing new programs, it is important to consider these barriers and how to lower them so that more marginalized students can participate.

B. Opportunities at Minority Serving Institutions

Historically black colleges and universities (HBCUs), Hispanic serving institutions (HSIs), tribal colleges, and native-serving institutions in the U.S. play a significant role in promoting racial and gender diversity in engineering [104]. For example, from 2001 to 2009, HBCUs consistently produced over 45% of all black engineering undergraduates at U.S. institutions [105]; yet only 15 of the 107 HBCUs have ABET-accredited programs as of 2021. Furthermore, HBCUs are known to produce large percentages ($\geq 40\%$) of black undergraduate degrees in other QISE-related disciplines contributing to diversity in most subfields (e.g., HBCUs produced an average of 25% of black CS undergraduates from 2001 to 2009 [105]). Here, evidenced-based strategies are presented for developing new opportunities in quantum engineering at minority-serving institutions through curriculum development, increasing participation in QISE and motivating engineering

student success at HBCUs, HSIs, tribal colleges, native-serving intuitions, and community colleges in the U.S.

In 1942, 20 years after the first quantum revolution, Dr. Herman Branson produced two works that focused on the training of black physics students and the need for a physics-aware workforce in the context of World War II [106]. He identified the need for qualified faculty trained in physics at HBCUs, and the development of new programs in physics at HBCUs. Today, although physics majors are being produced at an all time high in the U.S, the American Institute of Physics (AIP) TEAM UP Report the Time is now highlighted the success of HBCUs in producing African–American physicists despite their persistent underrepresentation in physics in U.S. institutions overall [50].

Similar to Branson's findings in 1942, there is now a need to train a new diverse workforce in the context of the quantum information revolution. Establishing new programs centered around quantum engineering at HBCUs can help achieve the overall goals of the U.S. NQI. Part of the larger strategy of the NQI is prioritizing the development of education and research activities through the establishment of collaborative research and education centers across the U.S. Recent examples exist of both U.S. government and industry-led efforts to direct resources to HBCUs where the majority of black undergraduates attain degrees in STEM [107]. Whether industry-led or supported solely by the government, new programs should utilize the best practices of Section V-A when engaging diverse communities in the context of addressing issues of belonging, providing research opportunities to students, and collaborating and engaging with HBCU faculty.

HSIs are institutions with at least 25% Hispanic undergraduate students. As of 2014, 13% of postsecondary institutions were classified as HSI, but enrolled 62% of undergraduate Hispanic students [108]. Furthermore, the Hispanic population is the fastest growing major racial/ethnic group in the United States, which suggests that the role of HSIs in training the STEM workforce will only increase as time goes on [50], [104]. This demographic trend indicates that implementing new quantum engineering programs at HSIs now could meaningfully increase the participation of Hispanic Americans in the quantum workforce in the long term. Some HSIs are also research-intensive institutions, but many are smaller, primarily undergraduate-serving institutions [108]. There are opportunities for partnerships between HSIs with and without engineering programs, enabling sharing of resources and curricula for introductory QISE courses between the two. Industry and government initiatives similar to those for HBCUs should also be considered for HSIs. Following this guidance, new programs in quantum engineering can expect to find that each subfield of QISE also benefits with respect to their overall diversity and equity efforts.

C. Transfer Pathways From Two-Year and Four-Year Institutions

Many engineering programs have connections with two-year community colleges and four-year institutions without engineering programs, and these partnerships provide an important pathway for students to enter engineering professions. In 2000, as many as 40% of students who received a bachelor's or master's degree in engineering attended a community college at some point [48]. Several studies have shown that transfer students are equally or more successful compared to nontransfer students in completing degrees in engineering [109]–[111]. Thus, this student group is the key to growing the quantum workforce. New QISE programs should build connections with existing partnerships where possible, for example, by helping community colleges implement an introduction to quantum science course (see Sections III and IV-B) or by offering summer internships for students. Building new partnerships with community colleges serving a large minority population should be prioritized [48].

Near-term opportunities abound for leveraging curriculum development efforts in QISE to create bridges between a more diverse cohort of students and careers in quantum engineering. For example, the introductory modules discussed in Section III intended for everyone (E) should be accessible to students at 2- and 4-year institutions with existing transfer pathways to established STEM programs. This could be realized as either reserved seats in classes offered at the destination institution with existing cross-registration agreements or offering the class at the transfer school with a guaranteed transfer credit, depending on local circumstances. If an effort is made to emphasize applications and potential career trajectories in QISE during these introductory classes, this approach may help build bridges from students unfamiliar with the STEM landscape to degree programs and careers.

D. Industry's Role in Promoting Diversity in Undergraduate Quantum Engineering

External stakeholders should provide powerful incentives to promote diversity, equity, and inclusion in undergraduate quantum engineering programs, which, in turn, will help to diversify the future workforce. It is first important to recognize that increasing diversity in industry promotes diversity in undergraduate education, and vice versa. In this section, ways that industry can work together with academia to expand and diversify the quantum workforce are highlighted.

Students from marginalized groups are more likely to apply for a particular major if they see their peers from that major being hired by industry [112]. Presently, the majority of employees at quantum technology companies have a Ph.D. in physics or engineering, but it is unlikely that the Ph.D. qualification will be needed for many of the positions required for a thriving quantum industry [12]. Industry can support the twin goals of workforce growth and diversification in several ways.

First, extra effort both by universities and industry is needed with respect to placing marginalized students in industry internships. This is because a strong predictor of whether a student will be hired by a company is if the student has completed an internship with the company as explored, e.g., in [113] and [114]. If internships are too limited, or not available at an undergraduate level, alternative programs such as participating in the open-source community (e.g., contributing to GitHub repositories or participating in hackathons) to

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get real-world coding experience may also improve chances of placement [112].

Second, industry must strive to democratize access to online training and resources (including quantum computing access) for quantum engineers, and in particular, focus on partnerships with MSIs, as discussed in Section V-B. In fact, this is already occurring in some places, for example, through the IBM strategic partnership with San José State University [115], the IBM-HBCU Quantum Center [107], and Google's related diversity and open-source initiatives [116].

Finally, industry and academic institutions need to continue benchmarking progress on improving diversity. For example, today in the U.S., the Quantum Economic Development Consortium already has the participation of companies to perform workforce surveys, so it is recommended that it expands its workforce development charter to track diversity metrics as well. The U.S. National Science Foundation has grant programs that can similarly evaluate student outcomes of academic institutions, and professional societies, such as the American Society for Engineering Education (ASEE), AIP, American Physical Society (APS), the American Chemical Society (ACS), etc., already play a large role in obtaining such statistics. Implementing periodic evaluation of academic and industry diversity initiatives is essential to ensure that programs meet their desired outcomes. Similar efforts can be undertaken in many nations throughout the world.

E. Summary of Diversity, Equity, and Inclusion Recommendations

These recommendations fall into three categories: 1) climate; 2) curriculum and program evaluation; and 3) industry.

First, regarding the climate for diversity, it is recommended faculty and industry research mentors be given training in best practices for mentoring, including building authenticity and trust with students and engaging in culturally aware communication that builds on students' strengths, since this is especially critical for the success of marginalized students [94]–[97]. Such training programs are available at many colleges and universities and where they are lacking can be leveraged from partner institutions. Departments developing QISE courses and programs should conduct periodic climate surveys of students and make them publicly available, to establish new best practices and continually evaluate what is and is not working. It is also very helpful to integrate high-quality undergraduate research experiences early (see Section VI). Longer, multisemester research experiences are preferable to short ones if possible [103].

Second, regarding curriculum and program evaluation, at minimum a quantum awareness or concepts course should be offered to introduce students to the field early, at the freshman or sophomore level. This is particularly important for institutions that do not offer engineering degrees but which have many students that transfer to engineering programs. This may also be applicable to other QISE fields, such as physics and computer science. In program evaluation, it is recommended to disaggregate all data on outcomes by gender and race/ethnicity. Instructors should consider implementing brief interventions in the classroom early in the semester to make the learning environment more inclusive and equitable [98]. Course and departmental goals around equity should focus on *equity of outcomes* for students, e.g., ensuring that marginalized students thrive in the program and, after completing their degree, have successful careers in QISE. A singular focus on recruitment should be avoided [97]. It is recommended that professional development (writing and culturally aware communication skills) be integrated into the required curriculum [95]. Quantum programs should restructure how and when the first year of quantum science is taught. Frontloading applications could make career trajectories more transparent (see Section IV-B). It is important to engage 2-year and 4-year institutions without engineering programs to open up transfer pathways [109]–[111].

Finally, regarding industry, it is recommended that students be provided equitable access to industry educational resources and internships, e.g., through formal partnerships with minority serving institutions. It is important to evaluate existing workforce needs and long-term goals and to communicate those needs to degree programs and curriculum designers. Industry can additionally develop credentialing pathways for marginalized students through internships and/or open-source educational materials.

VI. HANDS-ON TRAINING ON QUANTUM HARDWARE

Hands-on learning in QISE is the key to creating viable quantum engineers. Experimental research in QISE is extremely diverse; the tools used in quantum optics labs differ greatly from those used in microwave-controlled superconducting quantum circuits, for example. However, one of the chief opportunities of quantum information as a lens to view these experiments is its ability to link them with a common language. Educational labs that make this connection physical, as well as mathematical, by showing that similar experimental conclusions arise from experiments that look completely different, will help to develop a cross-disciplinary skill set and allow for a quantum workforce that can communicate across traditional hardware barriers.

Assembling and selecting hands-on labs for a quantum engineering course or program will not be a one-size-fits-all solution. Each program will have constraints, including budgets and faculty expertise. While plug-and-play resources in quantum engineering are available in some cases, many are expensive, while lower cost do-it-yourself approaches require significant expertise. Affordable hands-on training availability may depend on cross-institution exchange of expertise. For example, the Advanced Laboratory Physics Association (ALPhA) currently provides funds and structure for faculty members to exchange hands-on training on advanced undergraduate physics lab modules [117]; support for similar efforts in quantum engineering could be transformative for many fledgling programs.

The diversity of hardware modalities makes it impractical to effectively cover the breadth and depth of quantum systems that form the basis for current research and industrial R&D. Effective training strategies should therefore seek

to cover a core but limited collection of required knowledge, supplemented by a selected subset of more in-depth studies of particular platforms. The three major areas of QISE, communication, computing, and sensing, all involve preparation, measurement, and control of quantum states. Core components of hands-on training should therefore include an exploration of preparation, measurement, and control, while highlighting how quantum approaches differ from the classical techniques that are routinely covered in introductory engineering laboratory courses. Even if specific institutional barriers restrict hands-on lab work to a single platform, or if most of the interactivity comes from remote resources, adding simpler demonstrations of alternative platforms will provide students larger context by which it helps to understand the field. This section will provide examples of affordable approaches to cover these core capabilities.

A wide variety of platforms is included below. It is impossible to predict which platforms currently under investigation, or yet to be discovered, may end up being the best subject(s) for future quantum engineers. Therefore, inline with best practices in engineering education across engineering disciplines, it is important to train quantum engineers in general principles and design, not to be a technician on one particular technology. For this reason, programs should try to cover at least two platforms as part of the hands-on courses.

A. Optics

Quantum optics in the visible regime provides a relatively budget-friendly toolbox for lab activities, allowing students to gain hands-on experience with quantum state preparation, manipulation, and measurement. Many experiments can be performed using the polarization state of a laser beam as an analogy to a true quantum state, such as single-qubit state and channel tomography. It is possible to use classical laser beams to simulate QKD in a way that has lingering security loopholes, but gives students an interactive and tactile project making explicit use of many quantum-relevant features, such as superposition and measurement disturbance [118]. Student experiments with classical laser beams can also provide students with an essential toolbox of classical skills necessary in experimental quantum optics, such as optical fiber alignment and detection electronics.

For experiments that require quantum states of light, such as nonlocality experiments, spontaneous parametric downconversion of visible or near-ultraviolet laser light in a nonlinear optical crystal is a well-developed and affordable approach. There are many articles describing how to set up spontaneous parametric downconversion sources and related accessible optical experiments in quantum state preparation and measurement for students [119], [120]. The equipment needed is also available as a plug-and-play system from multiple companies, with costs currently on the order of U.S. $20k [121].[5]

Whether quantum or classically simulated, optics experiments clearly show how changes of the quantum state

impact measurement results. This is most simply accomplished through the polarization degree of freedom, where polarizers are used for projective measurement and combinations of half- and quarter-wave plates can be used to rotate states and measurements to arbitrary points on the Bloch sphere. However, the same effects can also be shown in space using Mach–Zehnder interferometers and time through Franson interferometry, although some effort will be required for stabilization in these degrees of freedom. Partial coupling between degrees of freedom, such as a birefringent crystal that couples time and polarization, can be used to simulate decoherence.

With quantum systems that feature single photons such as those generated by spontaneous parametric downconversion, students may show Bell nonlocality through violations of the Clauser–Horne–Shimony–Holt inequality, nonclassical photon correlation functions through Hanbury-Brown–Twiss interferometry, Wheeler's delayed-choice quantum eraser, photon bunching in a Hong-Ou-Mandel interferometer, multiqubit state tomography, entanglement-enabled QKD in the Ekert protocol, determination of one- and two-photon coherence times, and more [122]. Many protocols relevant to quantum information, such as the bulk optical C-NOT implementation and GHZ state creation, are also possible to implement, although they require specially tailored photon pair sources and/or multipair emissions, which may be prohibitively expensive or alignment sensitive for lab courses.

B. Atoms and Ions

Other possibilities for experiments with individual quanta can be contemplated with nitrogen vacancy center, neutral atom, or trapped ion hardware. Nitrogen vacancy centers, in particular, are well suited for sensing applications and demonstration kits are commercially available [123]. Complete demonstration kits at the level of individual quantum operations based on the other hardware platforms are not readily available. Compact and cost-effective hardware for laser cooling and magneto-optical trapping of atoms can be purchased [124]. Besides laser cooling, this type of hardware can be used for demonstrating quantum state control by optical pumping. The extension to experiments with single quanta using optically trapped atoms or electromagnetically trapped ions still requires substantial local expertise and infrastructure. Partnerships with industry could enable such laboratory experiences.

Ultracold atoms provide another setting where quantum phenomena, including superposition, interference, and tunneling, can be observed. The apparatus to produce Bose Einstein condensates is complex, comparable to a dilution refrigerator in cost, and not practical to maintain without locally available expertise [125]. An alternative is cloud access to a commercial machine that can be remotely operated [126].

C. Cryogenic and Solid State

Quantum solid-state platforms, such as superconducting circuits and quantum dots, require cryogenic operation at a temperature of 4K or lower, while experiments deep in

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[5]Mention of commercial suppliers is provided for information only and is not an endorsement of the products of a particular company.

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the quantum regime require dilution refrigerators to reach temperatures down to 10 mK. Such equipment is highly specialized and expensive ($300k is the entry level cost for a dilution refrigerator). Thus, deployment of dilution refrigerator experiments in an undergraduate laboratory will rely on local expertise or grouping the cost across regional schools. Similar to trapped ions and atoms, institutional partnerships could be essential to bring experience with such techniques within the grasp of students at a broader range of colleges and universities.

Higher temperature alternatives include implementing other types of cryogenic systems such as the Quantum Design Physical Property Measurement System (PPMS),[6] which can cool to 1.9K and thus would facilitate labs based on ancillary measurements such as superconducting transition temperatures or basic microwave resonator transmission data acquisition.

As an alternative that will help undergraduates gain familiarity with control of spins, techniques for manipulating and measuring them, and the terminology of coherence, experience with a pulsed NMR apparatus can be valuable. Complete setups are commercially available [127].

D. Nanofabrication

Nanofabrication is crucial to the creation of many types of quantum devices, including in photonic quantum computing, superconducting quantum computing, spin qubits, and ion traps. A laboratory or set of laboratories focusing on the design and implementation of a fabrication process for a simple device such as a lumped element resonator or Josephson junction would give students an understanding of the requirements of device fabrication, knowledge which is much needed in many implementations of quantum computing. Partnerships with nanofabrication facilities or groups with specialized equipment for qubit device design would augment student learning in this area.

E. Quantum-Classical Interface

All quantum technology requires a means of passing information between the classical and quantum domain, for instance, in the readout and control of qubits or quantum sensing devices. The quantum-classical interface (QCI) is a catch-all term for the electronic and optical subsystems of readout and control, such as data converters, amplifiers, signal sources, and digital logic responsible for generating and detecting readout and control waveforms, sequencing and synchronising them, as well as the infrastructure that connects those signal paths to the physical quantum devices that encode quantum information. Such infrastructure comprises cabling, packaging, optical fibres, chip-interconnects, resonators, and on-chip routing and multiplexing approaches that together constitute IO management between the classical and quantum worlds.

The QCI provides an important opportunity for hands-on training, making use of the classical software and hardware needed to support and enable quantum experiments.

Laboratory courses featuring microwave engineering, programming of embedded systems, signal generators, digitizers, and related hardware can provide skills of broad applicability for experimental R&D. It is worth noting that in the context of teaching, reasonably sophisticated electronics can be sourced for minimal cost in comparison to other domains of quantum hardware. Furthermore, such electronic subsystems provide an ideal platform for the development of generic problem solving skills, such as trouble shooting and debugging.

Modern communication systems and the engineering framework for their design provide a solid foundation for developing quantum control and readout platforms. Examples include modulation and demodulation techniques, nonreciprocal elements, noise mitigation, and approaches to bandwidth narrowing, for instance, using lock-in amplifiers for detecting weak signals. With respect to these topics, there is much common ground between electronic and optical or photonic systems. Indeed, radio frequency and microwave circuits (the basis for qubit control and readout) mix electrical and optical concepts and terminology. An ability to map and bridge these domains is a particularly useful attribute of the quantum engineer.

Moreover, the challenges associated with the QCI are likely to be major hurdles for the scale-up of quantum computers and quantum networks. The complexity of these systems over the next decade will rival the most sophisticated technological platforms ever constructed. Beyond the challenge of the hardware itself, quantum engineers must also simultaneously be able to work at various levels of abstraction, bridge fields, and leverage long-forgotten knowledge with new research discoveries.

F. Tools and Involvement From Industry

Undergraduate engineering education has a long history of using tools from industry in the classroom. For QISE education, providing the physical hardware to university students affordably and at scale is a challenge. However, within the quantum computing industry, innovations drawing from the infrastructure of classical computing have led to increased access to quantum computing resources. While not strictly hands-on in nature, these tools provide an opportunity for students to experience authentic quantum devices. These quantum computing tools can be categorized into either open-source software or hardware access via the cloud. Open-source software packages, such as QisKit [128], Cirq [129], and Katas [130], are essentially free for students and educators to use, and can be used to simulate quantum computers up to 30+ qubits on an affordable classical computer accessible to most undergraduate students. Furthermore, higher level libraries, such as TensorFlow Quantum [131], OpenFermion [132], and QisKit Aqua [133], can increase accessibility to students who are already familiar with machine learning or chemistry simulations.

For hardware access, companies, including AWS, Google, IBM, IonQ, and Rigetti, have made available some of their quantum processors for use via the cloud by the public and in the classroom. For example, IBM provides free access to their smaller systems, and Google has implemented batch execution

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[6]https://qd-europe.com/at/en/product/physical-property-measurement-system-ppms/

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of student assignments on their cloud systems. Although computer explorations are not a substitute for hands-on experimentation, for institutions that are not able to provide a laboratory experience, there are widely available and valuable educational tools supported by major companies in the areas of quantum computing and simulation. Companies, including Google, IBM, and Microsoft, provide extensive online tutorial material as well as quantum circuit simulators, among other publicly available interfaces. For example, IBM's QisKit platform provides free access to students wishing to experiment with quantum circuit design and in addition to simulation tools allows users to run examples on real hardware via cloud access.

In addition to the above industry tools, internships [134], [135] not only provide hands-on opportunities but can also provide the education and experience of working directly within industrial settings, which all have very different cultures and goals compared to academic labs.

VII. Summary and Key Recommendations

The rapid expansion of QISE outside of the research lab and in industrial applications necessitates the growth of a diverse workforce with increasing quantum knowledge and skills. The development of QISE applications, including communication, computing, and sensing, requires people at all levels from K-12 to the Ph.D. who are trained in quantum-related science and engineering. One strong focus of new training is at the undergraduate level for engineers. To facilitate the development and implementation of new quantum engineering education opportunities, an initial roadmap is presented for those creating these new programs, including suggested courses and modules, approaches to engage students in QISE training, and ways to rethink and create diverse, inclusive, and equitable education. These recommendations will enable bachelor's level engineers to achieve two levels of QISE training: 1) quantum aware and 2) quantum proficient.

Below, broad recommendations to consider when developing new quantum engineering education programs at the undergraduate level are outlined.

1) Traditionally, quantum courses and programs have been contained within physics departments. To prepare engineers for jobs in the quantum industry, new programs and training should be created in engineering departments with collaborations from science and math departments.

2) To create quantum-aware engineers, the authors have detailed, module by module, the development of a first QISE course for STEM students that can be implemented in many different academic environments. Such a course could be adjusted for different contexts, with additional modules, and would be sufficient for any engineer to obtain the minimum quantum expertise needed to participate in the QISE industry.

3) To create quantum-proficient engineers at a higher level than just being quantum aware, and at the current stage of the quantum industry, it is recommended that universities and colleges develop new minors in quantum engineering or tracks embedded in traditional majors, rather than full undergraduate degree programs. As the quantum industry grows over the next decade, full undergraduate degrees in quantum engineering may be desired and can be natural extensions of minor and track programs.

4) Minors or tracks in quantum engineering can be offered at many colleges and universities, as the authors suggest a minimum of only three or four new courses need to be created, with additional electives drawing from standard STEM course offerings.

5) The authors suggest a QISE course accessible to non-STEM students can be taught using very little math and instead focus on basic concepts and applications—QISE 101. This course can recruit students into a minor program, onboard students into the minor, and serve as general QISE education accessible to all STEM students from freshman year on. The focus on applications could make career trajectories more transparent to students as well. It is recommended that this type of course could be implemented broadly, including at community colleges and military schools, which could facilitate students' transition to a 4-year institution.

6) One important component to any minor program is hands-on experimental training, as many of the jobs in the quantum industry require this expertise. A variety of hardware platforms is recommended on which students can get this experience. Note that less expensive "classical" options, or partnerships with institutions with more resources, could help students at institutions with less infrastructure gain hands-on experience. Additionally, integration of high-quality undergraduate research experiences early in students' academic careers, with longer, multisemester research experiences being preferable, is recommended, as this will also improve diversity.

7) It is important to make sure these new courses and programs are effective at helping students to achieve the learning goals for the courses and programs. Toward that end, continued and expanded STEM education research is recommended be performed for QISE, especially the engineering context, to establish effective practices in this new domain.

8) As new programs begin to be developed, one has the opportunity to focus on creating a more diverse, inclusive, and equitable environment for students. There are several recommendations to help achieve these goals. Departments developing QISE courses and programs should conduct periodic climate surveys of students and make the results publicly available. This will help to establish effective practices and provide formative feedback to improve the programs. Aligned with this, it is suggested that course and program goals around equity should focus on *equity of outcomes* for students, i.e., degree attainment and employment, and avoid a singular focus on recruitment [97].

These recommendations, although ultimately reflecting only the authors, draw heavily on community input. As QISE engineering programs develop and mature based on ongoing

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education research, other programs in QISE fields will benefit from lessons learned. In particular, the "Quantum 101" course, if implemented, could provide data on how conceptual quantum science and technology can be taught in different settings, potentially providing an opportunity to modify current curricula within other QISE-related departments. Currently, there is a breadth of quantum physics education research that could be leveraged [57]–[64] but more must be done in the context of engineering fields. Additionally, because QISE is cross-disciplinary, additional QISE curricula and education research across a range of settings could inform course design and pedagogy within QISE fields outside of engineering.

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APPENDIX

The following brief glossary may be helpful in the reading of this article. For a thorough background on quantum information, the following texts aimed at general readers with some scientific background or knowledge are suggested [81], [136], [137].

1) *Analog Quantum Computer:* Sometimes called quantum simulators, these are a class of devices that leverage uniquely quantum effects to solve challenging simulation problems that are intractable for classical computers. The device is constructed to mimic as closely as possible a Hamiltonian of interest. Prominent examples include predicting the properties of high-temperature superconductivity and modeling photosynthesis [19].

2) *Decoherence:* The tendency of quantum states to be rapidly degraded due to interactions with their environment. This leads to the loss of superposition and entanglement. Decoherence is the major barrier to the realization of quantum computers, and if pushed to low enough levels, it can be overcome with quantum error correction.

3) *Digital Quantum Computer:* The common term for a universal quantum computer which can perform arbitrary quantum computations and is predicted to break RSA encryption, among other applications. The term often, but not always, implies error correction, qubits, and two-qubit gates, as an extension of classical digital computing concepts.

4) *Entanglement:* Nonlocal correlations between qubits that can only be present in quantum states. When a qubit is part of an entangled state, it does not have a well-separated state of its own, which implies enhanced mutual information. An example is

spontaneous parametric down conversion (see below) in which two photons resulting from the process separately have a random outcome (no information), whereas the joint measurement of both photons completely determines the quantum state (maximal information), in this case of their polarization states. Because of the original expression of this idea in 1935 [138], entanglement is often couched in terms of "spooky action at a distance," i.e., measuring one particle affects another particle when the two are entangled, even when physically separated by arbitrary distances—in this case the two photons. Entanglement does not allow for faster-than-light communication or information propagation.

5) *Hamiltonian:* The Hamiltonian is an operator that corresponds to the energy, and its average is the mean energy of the system. The Hamiltonian is the basic mathematical object governing time evolution of a quantum system, which, in QISE, often takes the form of a very large, even exponentially large, matrix.

6) *Hilbert Space:* The space of quantum states, which grows exponentially with the number of qubits. The principles of Hilbert space are the same as any linear vector space, such as the *x-y-z* of spatial Cartesian coordinates in three dimensions, except: a) the weights can be complex numbers, leading to phase interference similar to waves and b) the number of dimensions is very large.

7) *NISQ:* It is noisy intermediate scale quantum computing. This refers to the present and near-term era of quantum processors that are pushing the limits of classical computing, and possibly even surpassing them, but are limited in scope and do not yet have error correction.

8) *Nocloning Theorem:* The theorem proving an unknown quantum state cannot be copied. This is an important building block for secure quantum communications, as measurement (eavesdropping) of a quantum signal can be detected.

9) *Quantum Advantage:* The concept that QISE can offer computational advantages over classical systems. Alternate terminology includes beyond-classical, quantum primacy, and quantum supremacy.

10) *Quantum Circuit:* A discrete set of ordered quantum operations laid out in a grid, usually formulated in terms of gates on qubits.

11) *Quantum Dot:* A type of physical system that is often dubbed "artificial atom," because it features discrete energy levels. As a device, it is usually constructed from semiconducting material (typically silicon), and has locations where single electrons can be loaded controllably.

12) *Quantum Error Correction:* The procedure of encoding quantum information into multiple qubits using entanglement to correct for unwanted disturbances. The use of redundancy in these entangled states protects against errors. Unlike classical errors, which are bit flips, quantum errors are continuous. This, combined with the fact that measurement disturbs quantum states, makes quantum error correction a highly nontrivial process

compared to the classical case, where straightforward measurement (e.g., in a repetition code) can detect errors through majority vote.

13) *Quantum Optics:* The field studying and manipulating the quantum properties of photons, or light, and the interaction of light with matter.

14) *Qubit:* The quantum bit, which can be visualized geometrically on the Bloch sphere. The zero (one) of the classical bit is placed on the north (south) pole of this abstract globe. Quantum superposition is described by two angles between, a latitude and a longitude. Orthogonal states lie on antipodal points. The Bloch sphere construction allows for intuitive visualization of the evolution of qubits.

15) *Spontaneous Parametric Down Conversion (SPDC):* The conversion of a photon of higher energy into two photons of lower energy. SPDC is a standard way to generate entangled photons.

16) *Superconducting Quantum Circuit:* Electrical circuits made of superconducting materials, which, at very cold temperatures of tens of millikelvin, have a quantized Hamiltonian and offer the ability to encode qubits. Quantum computers based on such hardware are currently under development.

17) *Superposition:* Quantum mechanics allows the quantum state of a system to be described as a weighted sum of multiple basis states, for example, the 0 and 1 states of a qubit. Quantum states, including those with superpositions, can be manipulated and changed with quantum operations. Measurement destroys or "collapses" a quantum superposition into one of the basis states in the measurement basis.

18) *Trapped Ions:* Ionized atoms such as Ytterbium (Yb^+, Ca^+, Be^+, Ba^+, etc.) can be trapped and cooled such that isolated, controllable quantum states can be formed. Quantum computers based on such hardware are currently under development.

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