

Quantum technician skills and competencies for the emerging Quantum 2.0 industry

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Abstract. Quantum-based technologies have been instrumental in the development of a whole range of devices that are used these days (such as lasers, transistors, LiDAR, GPS, MRI, and many more). These technologies that emanated from the Quantum 1.0 Revolution have become ubiquitous in modern civilization over the past 50 years. The product commercialization and mass production were enabled by scientists, researchers, engineers, and most importantly, by the skilled technological workforce. This workforce played a critical support role in transforming inventions into high-volume, marketable products. We are currently at the heart of the Second Quantum Revolution, which is fueled by the research in quantum computing, quantum communication, quantum cryptography, and quantum sensing. The scientific progress that is currently taking place in these areas is going to fundamentally change the way we sense the world around us, approach our security, and process critical information. Governments and private entities across the world have recognized the strategic importance of quantum research-enabled technologies and have invested a significant amount of money to support graduate programs and research institutions where scientists, engineers, and other professionals are earning advanced degrees and immediately being engaged in active Quantum 2.0 research. To the best of our knowledge, and despite considerable investment in quantum research, no active efforts or programs exist that would train a quantum technological workforce at the technician level to support Quantum 2.0. The quantum industry, on the other side, has clearly identified the need for highly skilled quantum technicians that are able to support the commercialization of the new products and inventions. The lack of a trained quantum technician workforce is a major shortcoming that may have a profound negative impact on the long-term prospects and sustainability of the emerging quantum industry. The EdQuantum project, funded through the National Science Foundation (NSF) Advanced Technological Education (ATE) program, is an effort to close this shortcoming and propose a well-defined curriculum through which the incumbent photonic and laser technicians in the United States will be upskilled with the new skills and competencies from quantum research-enabled technologies. This paper presents the results of the first phase of the EdQuantum project—the quantum industry survey. Over the last few months, we sought input from the quantum industry as to what skills and competencies should a future quantum technician possess to support its emerging needs. The results collected during the survey are presented in this paper along with their impact on the proposed educational curriculum. This paper also elaborates on the alignment of the proposed curriculum with a few ongoing initiatives in the skilled technical workforce education (such as NSB Vision 2030, Convergence Accelerators Initiative, and Skilled Technical Workforce Initiative). © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.61.8.081803](https://doi.org/10.1117/1.OE.61.8.081803)]

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1 Introduction: Current State of Quantum Industry and Quantum Education

In December of 2018, the US Federal Government passed the National Quantum Initiative Act.¹ The goal of The National Quantum Initiative (NQI) is to build American leadership in quantum information science and technology (QIST). Federal agencies (NIST, NSF, and DOE) reported actual expenditures for research and development in quantum information science of \$449 million in 2019, \$672 million in 2020, \$793 million of estimated expenditures in FY 2021, and a requested budget of \$877 million in FY 2022.² On the legislative front, the National Quantum Initiative Act requires the NQI to “invest in activities to develop a quantum information science and technology workforce pipeline.” Other activities required by the Act include: establishing goals and priorities based on workforce gaps; assessing the status, development, and diversity of the United States quantum information science workforce and whether workforce concerns are being adequately addressed by the NQI; supporting curriculum and workforce development in quantum information science and engineering; fostering innovation by bringing industry perspectives to quantum research and workforce development, including by leveraging industry knowledge and resources; and supporting long-term and short-term workforce development in the quantum field.

The NQI has pursued these activities in large part through the National Science Foundation (NSF), which was authorized to create Multidisciplinary Centers for Quantum Research and Education. NSF has open funding opportunities in the area of advancing quantum education and workforce development.³ In addition, the White House Office of Science and Technology Policy and NSF have partnered with industry and academic institutions to launch the National Q-12 Education Partnership, designed to promote quantum outreach and training in middle school and high school.⁴

The Administration and Congress have acknowledged the pressing need to develop the domestic quantum workforce and have taken a variety of actions to begin addressing that need. In February of 2022, the National Science and Technology Council’s Subcommittee on Quantum Information Science released the Quantum Information Science and Technology Workforce Development National Strategic Plan⁵ that identifies key actions and gives recommendations in the following areas: developing and maintaining an understanding of the quantum workforce needs; introducing broader audiences to quantum science and technology through public outreach and educational materials; addressing gaps in professional education and identifying training opportunities; and making careers in quantum technologies more accessible and equitable.

Other countries have also heavily invested in quantum research both before and after the United States,^{6–8} making this a global race to capitalize on the significant progress in quantum research. While quantum computing may be headlining in major news outlets, there are many more advanced applications of quantum technologies worth mentioning, such as quantum encryption, quantum safe networks, quantum sensors, quantum dots, atomic clocks, quantum information processing, etc. According to the National Quantum Initiative, the Quantum 2.0 research can be divided into a few categories:¹ quantum sensing and metrology, quantum computing, quantum networking, quantum research to advance fundamental science, and quantum technology. These technologies span various industrial sectors that include national security, defense, finance, medical industry, data processing, automotive and aerospace applications, logistics, and cyber security. For example, a photon emission microscopy based on multiple quantum theories (Fowler-Nordheim tunneling, band gap engineering, Joule heating, etc.) is used in semiconductor industry to image individual transistor junction levels at feature sizes down to remarkable 10 nm (10 billionth of a meter) in fully operational integrated chip (IC) conditions.⁹ Quantum cryptography based on the quantum key distribution (QKD) is a technology that uses quantum physics to secure the distribution of encryption keys. New cryptographic techniques have emerged in recent decades that combine QKD with the quantum resistant algorithms as well as traditional methods to provide protection against quantum threats. The laws of quantum mechanics are used in quantum computing to create a qubit (quantum bit) that can

randomly be both in “1” and “0” state—the concept known as “superposition.” If properly implemented, this unusual property extends to any number of qubits enabling the entire computer to be in a superposition state, acting as a massively parallel computer which provides exponential computing power. This is a significant improvement compared to the classical computer that provides linear computing power. The task of controlling a massive number of qubits (which could be photons, NV centers, trapped ions, or electrons) is not an easy task; achieving this means establishing a “quantum supremacy.” Smaller-scale quantum computers already exist, albeit with a restricted number of qubits and great engineering challenges to overcome.

A broad impact of the quantum technologies on the economy is evident and critical—and we are not done yet. We are at the heart of the Quantum 2.0 Revolution with a very active research environment in the quantum realm. New scientific progress and inventions resulting from the Quantum 2.0 research will most certainly change the world dramatically in the coming years.

The federal government and agencies as well as private corporations have recognized the need to support and invest in graduate programs and research institutions that are actively engaged in quantum research. Through the National Quantum Initiative, three to six Quantum Innovation Labs are being established to serve as testbeds of collaboration between academia, government, and industrial scientists and engineers. Some large American companies working on quantum computers, technologies, and applications with large programs in place that support quantum research and education include the following: IBM,¹⁰ Honeywell,¹¹ Google,¹² Amazon,¹³ Microsoft,¹⁴ and Intel.¹⁵ IBM’s quantum projects consist of quantum processors, computers, and cloud-based services with access to software and simulation tools for workers, students, and educators at many levels. Honeywell Quantum Solutions has joined with Cambridge Quantum to form Quantinuum—one of the world’s largest integrated, stand-alone quantum computing companies. Quantinuum uses the trapped ion technology and so far, has built their customer-centric approach that includes hardware and software around the specific industrial applications they are serving. To enable new advancements in quantum computing, Google AI has created a complete campus in Santa Barbara, California, to be the home of their quantum data center, fabrication facility, research lab, and workspace. While they have large projects in software and cloud-based access to all things quantum, these corporations are also developing their own quantum hardware. There are also other, smaller startup companies, typically based on a technology developed over many years at various universities. These startups or smaller enterprises may have disruptive technology to scale quantum computing and other quantum technologies faster than even the large corporations. One such company is PsiQuantum,¹⁶ based in Palo Alto, California. PsiQuantum is focusing on the photonic approach to create a quantum computer. Its founders came from the University of Bristol and Imperial College in the United Kingdom.

Educational institutions are responding to the challenge of actively engaging in quantum research. Some universities that are growing quantum programs include the University of Southern California¹⁷ (USC), University of Wisconsin-Madison,¹⁸ Duke University,¹⁹ California Institute of Technology²⁰ (Cal Tech), University of California Los Angeles²¹ (UCLA), Massachusetts Institute of Technology^{22,23} (MIT), University of Arizona²⁴ (UA), Rochester Institute of Technology²⁵ (RIT), University of Colorado at Boulder²⁶ (UCB), and others. Many of these universities have received multiple grants from government agencies and are partnering with private and public companies as well as other university groups to reach the goals of their respective quantum research projects. A good example of this is the above-cited University of Arizona project that received \$26 million²⁷ to form and lead the Center for Quantum Networks (CQN) as part of its Engineering Research Center project. This grant includes collaborations with Harvard, MIT, and Yale along with member institutions University of Massachusetts Amherst, University of Oregon, Northern Arizona University, Howard University, University of Chicago, and Brigham Young University.

2 Need for a Collaborative Effort to Train Quantum Technological Workforce

Recent quantum breakthroughs and their commercialization have created a significant workforce gap that has left companies, national laboratories, colleges, and universities with a multitude of

open positions for people skilled with knowledge and experience in quantum technologies. Current open positions can be viewed on the various company, university, and recruiting websites. This gap in the skilled workforce impedes further progress of the US quantum industry. As much as it is of national interest to foster quantum research institutions at major universities, it is also of utmost importance to prepare the skilled technical workforce (STW) at the quantum technician level to support the commercialization of quantum products. The highly skilled technological workforce is traditionally trained at community colleges, and the emerging quantum field should not be an exception. Need for the quantum-smart workforce development is recognized in almost every act or policy related to the quantum technology. For example, the development of the workforce capacity to support the commercialization of quantum research-enabled products and applications has been recognized and encouraged in the latest Annual Report on the NQI progress (the supplement to the President's FY 2022 budget²). Excellent work has been done assessing the needs of the quantum industry for qualified professionals.^{28,29} Most of this research was, however, focused on quantum specialists with undergraduate³⁰ and graduate degrees in physics, chemistry, math, engineering, computer science, material science, and related technologies. Limited effort was given to assess the quantum industry's need for the quantum workforce at the technician level.

Surveys of the quantum sector show that companies are eager to hire workers not only with relevant knowledge but also with hands-on experience.²⁸ Such experience may be gained through laboratory coursework or through industry internships. The latter provides the student with real-world experience and can lead to full-time employment upon graduation. Apprenticeships are an alternative type of program that can connect classroom study and hands-on learning through partnerships between educational institutions and one or more companies.

The need for quantum-literate technicians will grow and evolve as quantum information science moves from predominantly research activities in academic or industry settings, often involving highly specialized equipment and components, to development and deployment in the field. As the industry grows and matures, test, measurement, and manufacturing processes will be standardized, and technicians will be essential to operations.

To support the commercialization of the current and future quantum-based products, more involvement of the advanced technological workforce is necessary. Professionals with technician skills traditionally support research labs, manufacturing lines, and test facilities as well as complement the skills and experience of scientists and engineers. As with any other new and emerging field, the quantum industry lacks this support structure; this gap is currently being filled by professionals who perform work that is below the level of their expertise. Scientists and engineers in quantum labs align the lasers, set the ion traps, adjust cryogenic systems, and perform other similar work that could otherwise be done by technicians with the appropriate skills and competencies. Embedding the quantum technician support structure into the quantum research labs and manufacturing lines will have the desired effect of freeing up time of those with more advanced skills to focus their efforts on the more critical engineering and scientific research activities.

The goal of the EdQuantum project supported through NSF ATE grant, DUE 2055061, is to close the above-mentioned gap and propose an educational curriculum through which the future quantum technicians will be trained to acquire both theoretical knowledge as well as practical skills and competencies to support the emerging quantum industry. Community colleges and other academic institutions across the nation will be given open access to the curriculum, instructional materials, laboratories, and other educational content developed through this project. It is widely believed that the seed for the new quantum workforce lies in the existing photonics workforce as optics and photonics are viewed as enabling technologies in the nascent revolution in quantum information science and technology.

The EdQuantum project is going to leverage the legacy and successes of our internal partner LASER-TEC, the National Center for Lasers and Fiber Optics Education. This center, whose executive director Dr. Panayiotou is a co-PI on EdQuantum, was founded through the National Science Foundation Advanced Technological Education Program back in 2013 to address industrial needs for skilled photonics, fiber optics, and laser technicians.

The proposed EdQuantum program can serve to grow the pool of talent at multiple levels and in multiple disciplines. Students in various disciplines, including physics, engineering, and computer science, may benefit from courses developed for those specializing in quantum optics and photonics. Programs at 2-year colleges sometimes provide a pathway into 4-year degree programs, particularly in engineering.^{31,32} Introducing courses in the fundamentals of quantum information science will help to address the broad needs of the emerging industry.

The first step in the EdQuantum project was to reach out to the quantum industry and collect the feedback on what skills and competencies should the future quantum technician possess to meet the demands of this emerging industrial sector. This paper presents the results of the corresponding quantum industry survey. The survey results are analyzed in detail and the takeaways presented in the following sections. It is our intention that, with this research, a methodical approach will be initiated to train advanced technological workforce at the technician level in the quantum research-enabled technologies to support the current and future needs of the evolving quantum industry. The results of the skills and competency survey³³ will be used to guide the development of the EdQuantum curriculum, courses, textbooks, and other educational content, as well as the quantum experimental labs at Indian River State College.

3 Proposed Quantum Technician Skills and Competencies

The EdQuantum team sought input from professionals currently working in the quantum industry, academia, and other stakeholders regarding the skills and competencies that a future quantum technician should possess to support the development and commercialization of new quantum products. The survey questions were created based on the industry input and then systematically organized into a few areas of interest—prerequisite skills in optics and photonics, quantum mechanics fundamentals, quantum hardware, quantum information theory, and fundamentals of spectroscopy. For each question, the survey participants were given four choices ranging from “definitely needed” to “definitely not needed” to provide their feedback as to what skills and competencies are needed by the quantum sector. Each section was open ended, should the survey participant wish to provide a descriptive comment or recommendation.

As already mentioned, the survey consisted of five sections that are briefly described below.

Prerequisite Knowledge of Optics and Photonics (5 Questions). Understanding theories and having practical, hands-on experiences with classical wave optics and the wave particle nature of light are essential knowledge prior to learning quantum technologies for technical applications. These skills and competencies are taught in the existing laser technology programs and can form the basis of future quantum technician knowledge. The basic topics in optics include reflection, refraction, polarization, and scattering of light. The main topics from physical optics identified in the survey include constructive and destructive interference, diffraction, and wave superposition. Hands-on experience consisted of Young’s double slit interference experiment and the knowledge of the main stages of laser operation that was pointed out as possibly important for technicians to know.

Fundamentals of Quantum Mechanics (4 Questions). The concepts of blackbody radiation, the photoelectric effect, the Compton effect, Heisenberg’s Uncertainty Principle, Bell’s inequality, photon entanglement, and quantum mechanical measurement accuracy limitations make up the topics in this section. Understanding and experiencing these will form the foundation of knowledge needed to build upon in various quantum-based applications.

Quantum Hardware (8 Questions). The key role of quantum technicians is to be able to set up and run various practical experiments deemed necessary to move quantum projects forward. This section focused on students’ hands-on abilities. Topics included setting up and running an apparatus for downconversion of photons and methods of optical fiber coupling to lasers and resonating cavities. Also, using cryogenic and vacuum systems are hands-on experiences inquired about in this section. Finally, the precision microscopy and surface profilometry and related measurement tools are areas of expertise asked about in the final question.

Quantum Information Theory (4 Questions). This section focuses on the theoretical and practical aspects of quantum computing, encryption, sensing, and related technologies. The following concepts are included in this section—quantum states, qubits, superposition, Bloch sphere,

spin qubits, super conducting qubits, quantum memory devices, and QKD protocols. Quantum computing programming is also specifically identified as a subject of interest.

Fundamentals of Spectroscopy (10 Questions). Spectroscopy plays a large role in many areas of quantum technology, and it is the least developed field for the laser technician education. At the same time, this industrial sector is relatively mature, with an ongoing need for technician skills and knowledge. There are more questions in this section as we seek to better understand the needs of our stakeholders in the spectroscopy industry. The questions include topics such as real-world spectroscopy applications and different types of spectroscopy techniques (absorption, transmission, fluorescence, reflectance, irradiance, and Raman). Also included are various types of spectrometer designs and instrumentation, such as FTIR, single and double monochromators, polychromators, MEMS, Bragg sensors, spectrophotometers, filter wheels, and photonic integrated circuits. There is a good mix of hands-on and virtual inquiries including best practices in the optics spectroscopy laboratory, standard spectrometer operations, and optomechanical assembly techniques.

After each section, a space was provided for the survey taker to provide comments about the section and another space was provided for general comments at the end of the survey. The survey was powered by Google Forms, and responses were collected, analyzed, and reported in this paper. The rationale for the questions in each of the five sections provided valuable feedback that would steer the development of the future quantum technician curriculum. The next section presents the summary of the survey results. More detailed survey results are available online and may be provided per request.

4 Industry Feedback on Proposed Quantum Skills and Competencies

The survey was conducted over the period of two months (November through December 2021). Quantum industry was contacted through internal collaborators as well as through existing networks of our external partners: Quantum Economic Development Consortium (QED-C), Quantum Industry Coalition, LASER-TEC, Optics and Photonics College Network (OPCN), Florida Photonics Cluster (FPC), Montana Photonics Industry Alliance (MPIA), and Central Carolina Community College Advisor Network. A few professional news media sources such as Quantum Computing Report and Optics and Photonics Education News (OPEN) also published short articles about the project and invited their audience to participate in the survey. The survey consisted of 31 multiple-choice questions, took about 15 to 20 min to complete, and was anonymous. The random respondents who responded to the survey were asked to categorize themselves into one of the following categories—industry, academia, legislator, or other. A total of 24 professionals responded to the survey and provided their valuable feedback. This response rate is considered satisfactory considering the relatively short duration of the survey, the busy schedule of the professionals employed in quantum industry, and a strong focus of the quantum researchers on the quantum research over product commercialization and workforce development. The affiliation breakdown of the survey respondents was 75% industry and 25% academia.

A detailed breakdown of the results for each question in each section is available and may be requested from the authors. A summary of the results of each section is provided in Fig. 1. In general, about 80% or more of the responses to the questions indicated that the skills and competencies described in the questions either definitely or probably should be taught in our program. While this is a good indication that we are on the right track, the details also provide the necessary feedback to begin organizing a priority list of topics in our courses and hands-on laboratories.

It is especially important to consider the responses selected as “Maybe Not Needed” or “Definitely Not Needed” if these together were at a scale of 20% or greater for a specific question. The first section on optics and photonics prerequisites shows that over 75% of the respondents indicated that the students entering the EdQuantum program “definitely or probably should” have the optics and photonics skills and competencies described in the questions. This is in line with a wide belief that the seed of the future quantum workforce lies in the current photonics workforce. Looking at the results to the individual questions, as shown in Fig. 2, over 30% of the respondents suggested that students’ ability to describe the main stages of laser

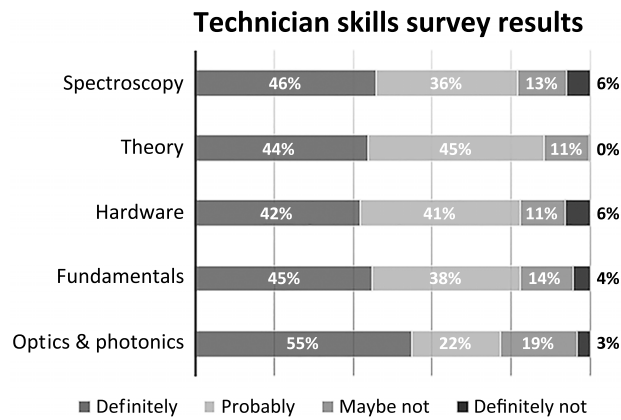


Fig. 1 Summary of the results collected in the survey. Please note that the chart above does not show the important details contained in the answers to the individual questions.

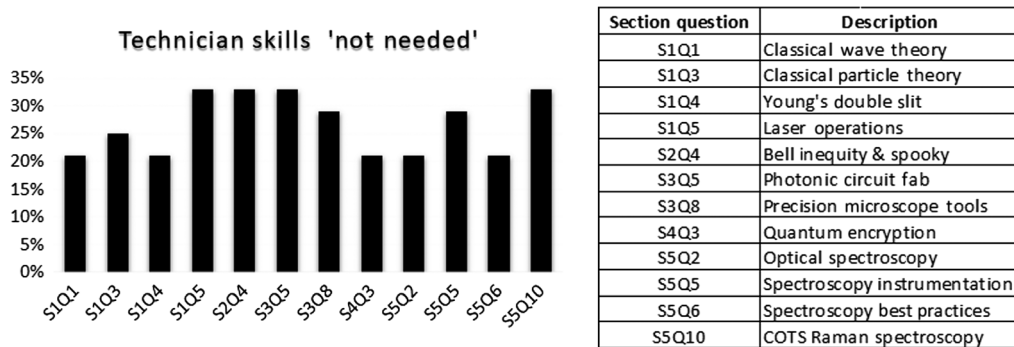


Fig. 2 Questions with responses over 20% “probably not important” or “definitely not important.”

operation are “maybe not needed” or “definitely not needed.” Respondents seemed to prefer practical (hands-on) skills in a laser setup and operation over the theoretical knowledge about the laser pumping, population inversion, photon seeding, and similar abstract education. The summary percentage results shown in Fig. 1 for the quantum fundamentals are similar to those for the prerequisite optics and photonics.

As shown in Fig. 2, 33.3% of the respondents indicated that the students “maybe do not” or “definitely do not” need to know about the Bell inequality or “spooky action at a distance.” These subjects seem to be too theoretical for the technician level, which is a similar trend observed to the one from Sec. 1. These details that are not reflected in the summary data are very important results from the professionals taking the survey and will guide us in the development of the theoretical parts of the curriculum. The other topics identified in Fig. 2 as being at a scale of 30% as “not important” will be reviewed in detail by the curriculum development team to determine how much time and effort should be spent on these subjects during the training of the future quantum technicians.

Looking at skills deemed “important,” the summary of results that pertain to quantum hardware are numerically similar to the other sections. Again, the details contain important distinctions.

For example, referring now to Fig. 3, 92% of respondents indicated that it was very important for students to understand methods of superconducting qubit fabrication—coherence and couplings. The other questions in this section were more evenly divided, and some comments suggested that hardware is dependent on the company and application. Survey results about quantum information theory (Sec. 4) show the highest importance overall, with 96% as “very important” or “could be important.” This is an indication that respondents view information and knowledge about quantum computing as one of their highest priorities. It is important to mention, however, that the survey results may have been skewed by a large participation of the survey

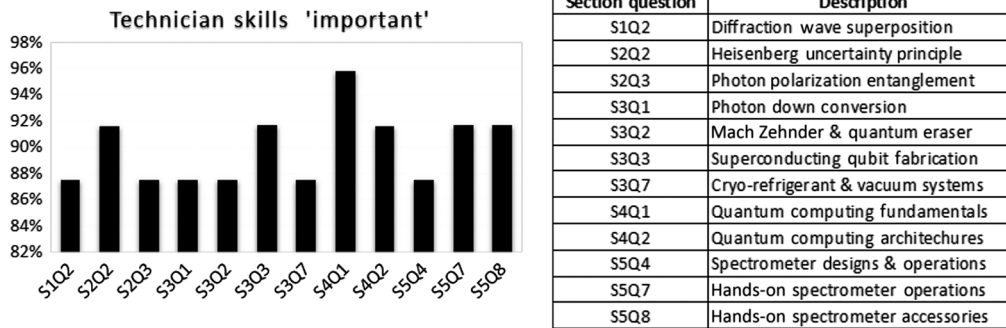


Fig. 3 Questions with responses over 85% “important.”

takers from the area of quantum information science. Nevertheless, this result will be considered during the curriculum development.

Spectroscopy, the final and longest section, shows mixed results starting with more even answers across the importance lines. The only exceptions are in the areas of spectrometer fundamentals and characteristics, best laboratory practices, optical alignment, filtering, and optomechanical assembly. These all show close to 80% “very important” or “could be important.” This indicates a high importance of traditional hands-on optics and photonics technician skills and competencies like those already taught to students in the laser and photonics programs across the nation.

The results shown summarily in this survey are explained in the comments provided at the end of each section and more generally at the end of the survey by some respondents. The diversity of written comments ranges from constructive criticism of the way the survey was written and the specific questions to great encouragement with a sense that we are tackling a very difficult subject with high expectations. From the authors’ perspectives, we are very grateful to all the respondents and will continue to use the results as guidance as we develop our courses. Table 1 shows some individual comments collected in the survey.

5 Future Steps: Developing EdQuantum Curriculum

Looking back over the process of developing this survey and reviewing the results, many key concepts have been revealed—some expected and some not. Figures 2 and 3 helped us identify the topics that the survey respondents indicated we should focus on as we develop the course materials as well as those topics that should be less emphasized. Unexpected results include the “not important” topics of classical wave and particle theories, Young’s double slit experiment, and laser operations. We also thought the topics of photonic circuit fabrication, using precision microscope tools, quantum encryption, and spectroscopy would rate higher. Some of these topics may be considered separately from the quantum courses, as they may be part of the laser electro-optics programs.

The changes in the emerging quantum industry may be slow at first as the hardware and software technologies for each application are developed and implemented. Then, like the differences between quantum and classical computing, the changes will be more dramatic with results seen in both financial and real-world experiences. The financial impact will be measured and tracked in the stock markets; however, the real work experiences will be varied and remarkable. Similar experience was observed in other industrial sectors, such as medical drug discovery for healthcare, logistics improvements, energy production and distribution, machine learning. While these opportunities are exciting but may be long far-fetched, the need for qualified quantum technicians is already here. Without them, the quantum journey will be slower than expected.

To develop a well-trained workforce in quantum technologies requires plenty of time and thoughtfulness, careful and methodical planning, and dedicated effort. This mission of

Table 1 Individual comments by the survey participants separated into the corresponding sections.

Prerequisite skills in optics and photonics	“Add dualism concept for the light.”
	“I believe a good sense of light and light properties is needed . . . with more of a functional understanding of how light works in optical and photonics settings.”
	“The math needed for making sense of some of the wave phenomena might be too hard for some community college students.”
	“Should focus more on polarizing elements such as wave plate polarizers and beam splitters.”
	“Basic understanding of Fock basis, photon distributions, different types of photonic states such as squeezed state.”
	“Understanding sources of noise, such as photon loss, dark count and single photon source inefficiency.”
	“Knowing what the laser does and how to use it is more important to know than how it works internally.”
	“Basic algebra and understanding ray optics in basic level.”
Fundamentals of quantum mechanics	“Single photon detection, and detectors is probably useful to know about.”
	“Add spin concept and modern consequences as spintronics.”
	“Deriving a Bell inequality is probably not as important as understanding the phenomena of entanglement and of superposition.”
	“Aside from a conceptual level, most quantum is very hard to deal with unless you have a strong math background.”
	“Entanglement is likely hardest section to put into practice well since the “uncertain” nature of everything in quantum mechanics is so outside our everyday experience.”
	“Should also have some notions of linear algebra connected to Pauli matrices and Kronecker products. And know about eigenvalues and eigenvectors and projection operators.”
	“Some technicians may not need to know about quantum mechanics at all to be useful. If they have good optics skills and knowledge, that is plenty.”
	“Should be familiar with basic concepts of QM, e.g., Heisenberg uncertainty principle, Hamiltonian, observables, superposition, etc.”
Quantum hardware	“Understanding of a single photon emitter, and uniqueness of a quantum state would be useful.”
	“High vacuum deposition techniques for optical surfaces are important.”
	“I would assume this type of knowledge would be one of last a student would take since they may have a specific destination in mind for employment.”
	“Include skills also in microwave and high frequency electronic technology and the associated measurement systems.”
	“These hands-on skills are fundamental to innovation in quantum tech.”
	“Depending on the type of hardware the skills could be different. For example, if the hardware is superconductor, understanding Mach Zehnder interferometer is not important at all. On the other hand, if the device is photonic, understanding of dilute refrigerator or vacuum chamber wouldn't matter.”
	“I think Diamond NV experiments are pretty accessible now, and could fit into a quantum technician laboratory more easily than some other experiments and can demonstrate important concepts.”

Table 1 (*Continued*).

Quantum information theory	"Students should be able to understand how quantum sensing and measurement works."
	"Students should have some skills in linear algebra and vectors in order to understand how qubits work."
	"Basic understanding of various qubit modalities would help to develop hardware-dependent algorithms which are aware of the dominant sources of noise."
Fundamentals of spectroscopy	"Students should know how to detect single photons, how we create sources of single photons and how one measures signals with homodyne or heterodyne methods."
	"Spectroscopy is a vast landscape of techniques and methods, quite large as it was one of the widely used technologies. It's a lot to cover during the course of a college degree."
	"Rather than teaching someone how to operate a specific machine, focus on a combination of general topics on how optics systems work (mirrors, lenses, filters, etc.) and some hands-on experience with oscilloscopes, photodiodes, building a beam path, etc."
	"The most important spectroscopy concept in QIST which is missing in this survey is the laser spectroscopy. This includes understanding linewidth and sources of phase and frequency noise in lasers, and the approaches required for frequency stabilization, linewidth narrowing, noise cancellation, etc."
Overall comments	"Students need to focus first on a strong conceptual base and ideas related to superposition, indeterminacy, entanglement, complementarity and measurement before learning more complex phenomena."
	"I'm not sure the [quantum] field is developed enough yet to determine the practical skills required in a technician."
	"I would love to know how these classes are received. I believe many more students would enter these fields if you didn't have years of drudgery/boring topics that you had to learn to get to the cutting edge and exciting stuff."
	"The topics listed are extremely important for quantum tech students if they expect to innovate future systems."
	"Different quantum hardware requires technicians with different lab skills. I would rather split the quantum hardware section into three core modules, superconducting, photonics and spin or solid state."
	"I think this survey addresses majority of the curricula and program materials required for a training quantum workforce at the technician level."

developing a skilled quantum workforce will be successful only if it is supported by a strong collaboration between the community colleges and other educational institutions, researchers from the quantum industry, federal agencies, and legislators.

The goal of the EdQuantum project is to initiate the process of the quantum workforce development, to create the first-ever curriculum in the quantum technologies for technicians, and to encourage more involvement by other academic and industrial stakeholders in this important mission. It is anticipated that graduates from the EdQuantum programs, such as their predecessors in the LASER-TEC programs, will find many job opportunities in the quantum industry and government-funded laboratories.

It is also anticipated that the EdQuantum curriculum will consist of three semester-long courses. Each course will be backed by a textbook, lab experiments, and various course activities offered by an online learning management platform with open access. The course learning outcomes will closely follow the skills and competencies used in the survey with certain updates based on the feedback provided by the survey participants. The curriculum will consist of theoretical education and hands-on activities, both targeting specific quantum skills and competencies.

The theoretical portion of the curriculum will be a cohesive sequence of lectures, analytical exercises, simulations, and examinations. This curriculum will be developed following all of the

well-established pedagogical standards that promote an effective and inclusive learning environment. The curriculum content and delivery model will be tested and validated through courses offered in real time to the targeted audience and promoted through collaboration with academic partners and local industry. The goal of each hands-on activity is to bring complex quantum phenomena closer to the course participants by exposing them to both the industrial equipment as well as the existing educational kits developed by the quantum industry to be used for educational purposes. The course participants will be required to complete the hands-on portion either as a multi-day workshop at Indian River State College or at a location close to where most of the students are located. The project also intends to develop remote access to some of the established laboratories. This would enable hands-on training at a distance if the lab equipment permits such an option.

6 Alignment with the NSB Vision 2030 Roadmap

This roadmap³⁴ offers four sets of recommended actions that the National Science Board (NSB) believes the United States must take to achieve the goal of remaining the world innovation leader in 2030.

The Vision 2030 roadmap addresses key questions that include “How can American discoveries continue to empower US businesses and entrepreneurs to succeed globally?” as well as “How can the US increase STEM skills and opportunities for all Americans?” and “How can America keep its lead in fundamental research?”

As an NSF-funded program, EdQuantum has a goal of establishing quantum program learning outcomes geared toward achieving skills and competencies critical to support the National Science Board Vision 2030 Roadmap. To meet that goal, the EdQuantum project will work closely with university and industry partners as well as other government agencies in seeking their input and guidance on our curriculum, hands-on laboratory experiments, virtual capabilities, and overall science and technology requirements that our students should experience. Quantum technicians trained through the EdQuantum curriculum will be considered an active part of the smart workforce capable of supporting the quantum researchers, scientists, and engineers. The project will seek partnerships with the research institutions and universities through which the EdQuantum students will be involved as a support force in the quantum research. This is a win-win scenario for both sides as the quantum scientists will be given an opportunity to outsource simple lab tasks to the quantum technician trainees while the trainees will be exposed to a valuable experience of working and supporting a quantum research lab.

The EdQuantum project will specifically develop STEM talent for America by researching any ongoing quantum educational efforts at a middle and high school level using the support structure and network of our partners such as LASER-TEC. To develop a smart workforce, the EdQuantum will integrate into the curriculum higher-level skills such as critical thinking, problem-solving, creativity, and digital literacy as well as the STEM pedagogy and practices for diversity and inclusion. To help fill the quantum education pipeline for future years, the EdQuantum project will use educational tools and recruiting networks for K-12 so EdQuantum students, teachers, and professional industry volunteers can work with K-12 educators in their local regions to prepare K-12 students for college and university programs that include quantum technologies. To expand our outreach across the country, the EdQuantum team will leverage the assets of the Optics and Photonics College Network (OPCN)—currently consisting of 44 college programs in 29 states (see Fig. 4)—to promote the quantum educational content.

Finally, to support the global science and engineering community, the EdQuantum project will seek partnerships with compatible educational institutions in Canada and Europe. Such a collaboration has already been established with the Institute for Quantum Computing at University of Waterloo³⁵ regarding curriculum and materials for teaching quantum science to high school students. A future EdQuantum efforts may involve reaching out and cooperating with professional societies such as SPIE and Optica as well as with photonics clubs at colleges and universities in Central America, South America, and the Caribbean to share our curriculum and materials for teaching quantum science.



Fig. 4 Map of LASER-TEC Optics and Photonics College Network (OPCN) partners and collaborators.

7 Alignment with the NSF's Convergence Accelerators Initiative

Launched in 2019,³⁶ the NSF Convergence Accelerator program focuses on application-oriented research and discovery through team integration from industry, academia, nonprofits, government, and other communities of practice.³⁶ The examples supported by the accelerator incorporate those with the long-lasting societal impact including, but not limited to, integration of a solution into existing systems, creating open-source tools and knowledge products, and expansion of offered solutions into adjacent and new markets. EdQuantum is aligned with this initiative as its main product is going to be an open-access curriculum with various educational tools and hands-on laboratory educational materials. These new materials will allow incumbent photonics students to be upskilled in quantum technologies and find career paths in adjacent industries not necessarily typical of the laser, optics, and photonics industry. These career paths will have a profound societal impact as the new industrial sector, strategically important for the US economy and national security, is strengthened with a trained and highly skilled quantum technological workforce.

8 Alignment with the Skilled Technical Workforce Initiative by the National Center for Science and Engineering Statistics

The main focus of the Skilled Technical Workforce Initiative clearly lies on the STW,³⁷ defined as the professionals with STEM skills and knowledge who do not have a bachelor's degree. Through the efforts of the National Science Board (NSB) Task Force regarding the STW, the challenges as well as the opportunities have been identified that face students, incumbent workers, businesses, educators, and others involved with the STW.³⁷ The task force recommended four areas that need change to improve the state of the STW: change the message to emphasize the importance of the STW to our nation's economy; focus on the data collected nationally on the education, skills, and workforce characteristics of the STW; leverage the portfolio of federal investments; and, finally, build partnerships between K-12 school systems, 2-year colleges, 4-year colleges and universities, and other postsecondary education and workforce development programs.

The focus of the EdQuantum program is the development of an STW, at the technician level, for emerging quantum industries. The EdQuantum project aligns its efforts with the Skilled Technical Workforce Initiative in multiple ways. The mission of the project is not only to develop a well-crafted curriculum to serve the industry needs but to also disseminate its content effectively and dynamically to the industrial and academic community at large. In that regard, the goal

of the EdQuantum project will be to change the narrative and to emphasize the importance of the smart workforce development on the long-term prospects of the emerging quantum industry. The EdQuantum team is going to leverage the legacy of LASER-TEC and its Optics and Photonics College Network partners (OPCN) in the area of public messaging and relationships. The targeted categories will consist of precollege students and parents, college students and graduates, educators, veterans, industry (employers), unemployed, and career changers. Because the EdQuantum program will build on the skills and competencies of those typically learned in the lasers and photonics programs, the public relations messaging from the EdQuantum program will acknowledge such an educational background of the targeted audience and will modify the message by asking questions like “why follow the study of lasers and fiber optics with quantum technologies?” The messaging in the EdQuantum website and related marketing materials will follow the concepts and flows of the LASER-TEC website with changes that reflect the specifics of the quantum path. The EdQuantum team will use the same data collection methods used in the LASER-TEC Evaluation Reports³⁸ to provide data to the NSF and other stakeholders. EdQuantum has used the LASER-TEC relationships as a starting point and has begun reaching out to new contacts in the quantum industries, government agencies, and academia to share this data and further develop tools for public use and workforce planning.

The EdQuantum team has also started the process of building partnerships with federal agencies, quantum companies, and various consortia and coalitions who have a stake in the development of the quantum technical workforce. The Quantum Economic Development Consortium (QED-C) established by NIST, Quantum Industry Coalition, and various federally funded universities and national laboratories are becoming part of the EdQuantum’s growing network of partners. The quantum researchers and scientists who serve on the EdQuantum Advisory Board assist the EdQuantum management team in multiple areas including the development of the new educational course content and the establishment of the new infrastructure to teach the courses both locally and at other schools around the country. This paper is an effort aligned with the STW Initiative as it is an example of the following: publicizing and informing stakeholders about the state of the STW in quantum field, building awareness of the demands and challenges to be faced in the development of the future workforce, and providing opportunities to initiate collaboration across the nation with other schools with the focus of engaging in educational efforts directed toward the training and development of the skilled quantum technical workforce.

In addition to its own new network of external collaborators, EdQuantum will leverage the existing LASER-TEC partnerships with K-12 school systems, 2-year colleges, 4-year universities, and other workforce development programs in local areas near the schools affiliated with our past and present programs to expand into the future and provide quantum technicians for research and industry. Such LASER-TEC partnerships³⁹ include 162 companies with photonics clusters in Florida, North Carolina, Arizona, Colorado, Montana, and New York. EdQuantum will work with organizations such as Inside Quantum Technology⁴⁰ to help build new partnerships in the quantum world both nationally and globally. Some key industrial sectors these entities represent include medical, finance, telecommunications, automotive, aerospace, defense, artificial intelligence, computing, logistics, cybersecurity, etc.

9 Conclusions

The US quantum industry, Federal government, and higher education institutions have been moving forward at a fast pace in the global race to bring quantum technologies to practical advanced solutions in a wide range of application fields. In “Preparing for the Quantum Revolution,”⁴¹ an important discrepancy between the desires of the quantum industry and the preparations being carried out by many higher education institutions was discussed. Fox et al.⁴¹ found out that most institutions are considering masters programs in quantum information science. On the other side, the quantum industry has suggested that they would benefit the most from a one- or two-semester course added to any number of current engineering programs. This supplemental course offering in the quantum field would then train a broader group of traditional engineers, at a faster pace and lower cost, that would propel the quantum research and assist associated quantum companies with the commercialization of new products and their faster market adoption.

Conceptually, this is the path the EdQuantum program is taking at the 2-year college level—presenting a fast-paced curriculum consisting of no more than three courses to upskill the photonics technicians. Through this educational effort, the trained technicians will be readied to face the challenges of the Quantum 2.0 Revolution and support the demands of the emerging quantum industry. Implementation of the EdQuantum training is anticipated to be nationwide wherever the clusters of the quantum industry exist or are being formed. By understanding the successful roles laser photonic technicians have in industries and building from there, EdQuantum is preparing to add a few courses and hands-on laboratories to upskill their capabilities to enter the quantum workforce, ready to contribute with significantly reduced on-the-job-training. This approach would save the companies and the industry considerable time, money, and frustrations typically associated with training the incumbent workforce in adopting new advanced technologies.

As discussed in this paper, the EdQuantum program is aligned with a few ongoing national initiatives in the STW education effort (specifically NSB Vision 2030, the Convergence Accelerators Initiative, and the STW Initiative) with the goal of ensuring that best practices in STEM education are implemented. The results of the quantum industry survey presented in this paper indicate that the EdQuantum project is on a good track in meeting its goals and objectives. Continued discussions with our advisors, partners, collaborators, and college network instructors will supplement the survey results obtained and reported in this paper. This collaboration is strongly believed to be crucial to the success and to the achievement of the goals and objectives of the EdQuantum project.

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