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Invited Paper

Quantum education: How to teach a subject that nobody fully understands

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ABSTRACT

Quantum technologies are expected to be among the most transformational technologies of the twenty-first century, changing how we sense the world around us, approach security, and process critical information. Transitioning the industry from quantum research labs to the commercial environment requires a sizable workforce skilled in supporting Quantum 2.0. To achieve the goal of the entire quantum ecosystem, society at all levels needs to be aware of this emerging field and then be inspired, attracted, educated, and trained with the new quantum skills and competencies. This poses a challenge as quantum science is a difficult and counterintuitive subject. How is a subject such as quantum mechanics that, as the famous quantum scientist Richard Feynman once said, "nobody fully understands" to be taught?

In this presentation, we will share our experiences and results of EdQuantum, an NSF-funded project whose goal is to develop a curriculum to train future quantum technicians. The proposed curriculum intends to provide an essential first step in quantum education at the associate's level. The curriculum relies heavily on a visual, hands-on approach that is based on commercially available quantum educational hardware. The curriculum strives to bring complex quantum science to a level understandable to individuals without a solid scientific background through algebra-based theory and simple experiments. As such, it may also be used to raise awareness and inspire high school students to seek careers as future quantum scientists.

Keywords: quantum education, quantum workforce, quantum experiments, quantum hardware, high schools

1. INTRODUCTION

Recent scientific breakthroughs in quantum sensing, quantum computing, and quantum networking are paving the way for quantum technology to be one of the most disruptive technologies of the twenty-first century, impacting almost every aspect of our daily life [1, 2]. Advances in quantum computing, for instance, have already resulted in hardware and software capable of simulating complex systems in chemistry, optimizing portfolios in finance, and developing new algorithms in material science. Scientific work in quantum cryptography produced new secure methods of transmitting data in the public domain without fear of unauthorized interception. Quantum sensors have reached new levels of accuracy that allow previously unimaginable and novel applications such as the detection of gravitational waves in astronomy, accurate sensing of magnetic fields in mining and mineral exploration, and precise measurement of acceleration in seismology, navigation, space exploration, and construction.

Undoubtedly, quantum technology has the potential to make a profound and long-standing impact on the global scene, and as with any other emerging technology, our society should be prepared to respond proactively to the challenges of the Quantum 2.0 revolution. All segments of society should be made aware of the unavoidable changes that quantum technology brings and then be inspired to participate in a responsible manner. Society should be educated about the potential benefits and risks of quantum technologies. This should be a multidimensional effort that includes: (1) the most general public outreach to raise awareness about what quantum is and what quantum is not, (2) the efforts to attract and inspire the next generation of young quantum scientists at local high schools, (3) targeted training of the future quantum technician workforce at community colleges, and (4) the development of strong undergraduate and graduate educational programs in quantum information science to support the quantum scientific research [3, 4].

Creating a sustainable education in quantum science brings a few unique challenges to this field. Quantum mechanics is considered, by many scientists and nonscientists alike, counterintuitive. This is because quantum particles, responsible for quantum phenomena and utilized in quantum devices and systems, behave contrarily to what classical physics teaches us. For example, a quantum particle can exist in multiple states simultaneously that change if measured or observed with a certain predefined level of measurement inaccuracy that is not measurement device dependent. How do educators teach a subject that, as the famous quantum scientist Richard Feynman once said, "nobody fully understands"?

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In the era of social media swarming with conspiracy theorists, how can we reconcile the laws of classical physics taught in traditional educational programs with the laws of quantum mechanics that may appear fundamentally opposed to our perception of the macroscopic world? The role of educational institutions and especially experts in quantum science engaged in the academic or scientific community is critical in addressing the above challenges. Only through a concerted institutional and individual effort will the mission of bringing quantum technology closer to the hearts and minds of a larger audience be accomplished.

2. RAISING QUANTUM AWARENESS IN LOCAL COMMUNITIES

To address the challenge of the counterintuitive nature of quantum mechanics and create quantum education and outreach that inspires, educators should explore innovative ways of introducing quantum concepts. These new instructional methodologies directed toward a general audience must significantly differ from the typical pattern of teaching quantum in a traditional calculus-based undergraduate quantum mechanics course. This is because the target audience does not only consist of physics and engineering students. The new quantum ecosystem spans diverse profiles, ages, and educational backgrounds and encompasses future quantum scientists, quantum users, and quantum-to-be-aware stakeholders [3].

To introduce quantum technology, educators should start with more straightforward concepts and ideas easily understandable by the audience with no scientific background or prerequisite knowledge of quantum mechanics. Many real-world examples illustrate how quantum technology is being used today. For instance, it can be discussed how quantum computers are used to optimize supply chains or develop new drugs or how quantum cryptography is used to secure communications. Covering applications of quantum technologies and industrial segments impacted by quantum breakthroughs may inspire further exploration of the subject.

Next, the fundamentals of quantum mechanics could be introduced, such as the wave-particle duality and the concept of superposition. From there, an educator may move on to more complex topics like entanglement and quantum algorithms. To introduce more complex subjects of quantum mechanics, analogies could be utilized to make abstract concepts more relatable to a general audience. For example, one can use the analogy of a coin flip to explain the concept of superposition or the idea of a lock and key to describe how quantum cryptography works. An educator must use this analogy-based instruction carefully because analogies can sometimes create an incorrect and oversimplified picture of a complex concept, causing more harm than benefit in the educational pursuit of the future quantum scientist.

Figure 1. Indian River State College students present quantum and photonics equipment to the local community residents during a public outreach event at Massey Campus in Fort Pierce, Florida (April 12, 2023).

It is a common misconception that quantum mechanics is hard to visualize as it involves phenomena that are not visible to the naked eye. Many visualization tools are available these days, both in the commercial and public domain, that can be used to make quantum concepts more tangible. For example, one can use animations to show the behavior of particles in a superposition state or 3D models to demonstrate the structure of quantum circuits. Interactive activities like games and simulations can help engage a general audience and make quantum technology more approachable. There are already games that simulate the behavior of particles in a superposition state or virtual labs where people can experiment with quantum circuits [5].

3. THE ROLE OF COMMUNITY COLLEGES IN QUANTUM EDUCATION

According to the American Association of Community Colleges, 1,038 community colleges nationwide served over 10.2 million students in the fall of 2021, with an average annual tuition of about $3,860. About 34% of all community college students attend their academic institution part-time, with many simultaneously balancing employment and education [6]. Community college students span a widely diverse range of profiles and ages. Almost half the community college student population belongs to the 22+ age group. Mixed ages and educational backgrounds create unique dynamics in community college classrooms. Community college faculty must implement various methods to tackle differences in short and long attention spans, the unique perspectives of Gen-Y versus the to-be-upskilled workforce and career-transitioning middle-age students, and so on. 55% of minority students enroll in community colleges due primarily to their open-door policy, accessibility, and focus on students and teaching. Since their inception in the early 1900s, and with their rich heritage, community colleges continue to provide opportunities for higher education to all Americans, enabling many to live the American Dream [7]. Community colleges also offer a wide range of benefits to the local communities, from providing accessible and affordable education to contributing to the prosperity of the local economies.

The twenty-first century has been marked by rapid technological innovation and transformation across many sectors, including artificial intelligence, robotics and automation, and quantum. Technology is accelerating faster than our ability to adapt [8]. As a result, a clear distinction between educational efforts during college years and the pursuit of career opportunities after graduation becomes less clear. To stay current with the rapid technological changes, one must continue learning while working through various on-the-job training and professional development opportunities. These external forces will ultimately impact higher education, including community colleges. Traditionally, community colleges focus on workforce training to support industries in the last stage of product development—commercialization and mass production. To support rapid technological changes, community colleges of the future must adapt to changes and be more exploratory and less reactive. Advanced technological programs at community colleges of the future must be more engaged in emerging technologies developed at start-up companies and research labs. The curricula must be upgraded to introduce research-oriented high-level skills and competencies and shift the classroom dynamics from the "hands-on obsession" to "brain-on exploration." Not all emerging fields and technologies will necessarily translate into mass-produced products and services with a high workforce demand. However, those emerging fields that evolve into tangible workforce demand will move at such a fast speed that educational institutions will struggle to follow if not engaged from an early stage of the technology inception. Exploring multiple technologies through academic research will probably be affected by institutional constraints. More cross-institutional collaboration is thus necessary to mitigate institutional constraints such as lack of faculty expertise or limited departmental budgets.

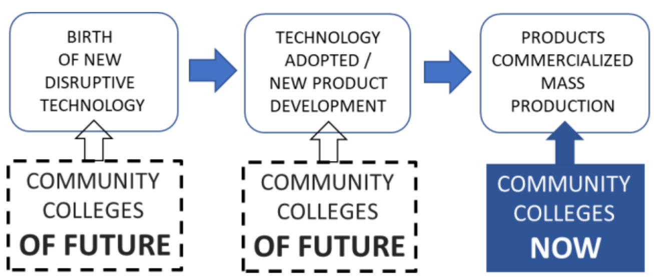

Figure 2. Reinventing the mission of community colleges of the future.

Community colleges should also take a more prominent role in K-12 STEM education, directly supporting the development of a broader quantum ecosystem by inspiring and preparing high school students to become future quantum scientists. The involvement and presence of the college faculty in high school science classrooms must be increased. The high school administration must be engaged in discussions about how to support quantum outreach and what role the high school teachers should play in such efforts. New avenues must be found to motivate, engage, and train high school teachers to become advocates of the quantum revolution. High school students should be offered new educational pathways in quantum technology that are broken up into weeklong workshops and lead to stackable skill-based micro certificates.

Quantum technology, one of the emerging technologies of the twenty-first century, will require strong support from academic institutions, including two-year colleges. The quantum industry is evolving as a geographically-dispersed and emerging industry with limited support from local or regional educational institutions. As such, quantum education at the community college level is literally nonexistent. A few well-established programs offer two-year education in quantum-enabling technologies such as laser technologies and precision optics. Only a few community colleges nationwide are exploring quantum education with Indian River State College leading the effort to establish the first-ever quantum curriculum for technologists [9]. The quantum industry has no other alternative than to draw talent from other geographical areas, paying significant fees to cover the relocation of new hires. To address the current shortage of qualified technicians in quantum technologies through existing programs, two approaches may be implemented: the "Education Goes to Industry" (EGI) approach or the "Industry Comes to Education" (ICE) approach. The EGI approach is based on delivering long-distance education to the local workforce where the industry is located. This approach can be achieved through online programs, remote access to geographically-distant laboratories, and on-the-site training using portable educational kits. It would require increased faculty mobility, mobile laboratories in trailers, and suitcase-size portable quantum equipment. The ICE approach is based on sending the local workforce to the geographically remote program to attend on-the-site training at the host institution. The theoretical portion of the curriculum could be delivered through an online approach. The attendants would be trained by using cutting-edge quantum equipment at the host college through intensive education leading to a certification in quantum technology. This approach would require the employer to cover the travel cost of the trainees. It promotes increased mobility of the quantum workforce and may need minor updates to the host community college infrastructure. The two approaches, briefly described above, are by no means the sole options to support the quantum industry through a community college education. However, they provide short-term support that can reduce the shortfall of qualified technologists in the field of quantum technologies and quantum-enabling technologies.

Figure 3. The geographical distribution of the quantum industry. The data represents the state of distribution as of December 2022, collected through multiple sources.

Specific changes must occur at community colleges to create a prosperous environment and to ensure future roles for these academic institutions in quantum education. First, college faculty supporting quantum education must be research driven and cultivate an exploratory mindset. A well-established and robust connection with the quantum industry will be preferable. The instructors must be engaged and adequately motivated to perform both teaching and research. Their role would include continuous development and upgrades of the quantum curricula and course material with severe constraints due to the need for educational content in emerging and developing quantum technology. The faculty in the quantum educational programs must have clear institutional support that starts with institutional awareness of the impact of quantum technology on the local communities as well as society at large. The administration must allow the faculty's travel activity that promotes cross-institutional collaboration and leverages constrained resources. The administrators must establish the institutional infrastructure that enables shared teaching-research assignments of the faculty. Finally, precise performance metrics must be reinstated to incentivize and reward creativity and extra effort by the instructors.

4. EDQUANTUM CURRICULUM AT INDIAN RIVER STATE COLLEGE

Indian River State College has undertaken the ambitious role of pioneering the introduction of quantum science into advanced technological education at the community college level. The EdQuantum project, funded through the National Science Foundation (NSF) Advanced Technological Education (ATE) program, is an effort to propose a well-defined curriculum through which the incumbent photonic and laser technicians in the United States will be upskilled with new skills and competencies from quantum research-enabled technologies [9]. This is done by developing, testing, and disseminating a three-course hybrid curriculum in quantum-enabled technologies. The proposed quantum technician curriculum is a cohesive sequence of lectures, analytical exercises, experiments, simulations, and examinations following all pedagogical standards in an effective and inclusive learning environment. Each course will be taught in a hybrid format consisting of the theory in an online, open-access environment and the hands-on practice (capstone) offered through short workshops at the host institution or an industrial site.

Through an extensive survey, the EdQuantum team sought input from professionals in the quantum industry, academia, and other agencies and consortia 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, fundamentals of quantum mechanics, quantum hardware, quantum information theory, and fundamentals of spectroscopy. Based on the survey results reported [10], the EdQuantum team constructed the EdQuantum curriculum framework with top-level competencies and lower-level course learning outcomes [11]. The main guidelines used in the development of the EdQuantum curriculum are: (1) to use no calculus or hard math, (2) to be as intuitive as possible, (3) to lead to a formal quantum certification, (4) to be as applicable as possible, (5) to cover both quantum software and quantum hardware, and (6) to promote inclusiveness and diversity.

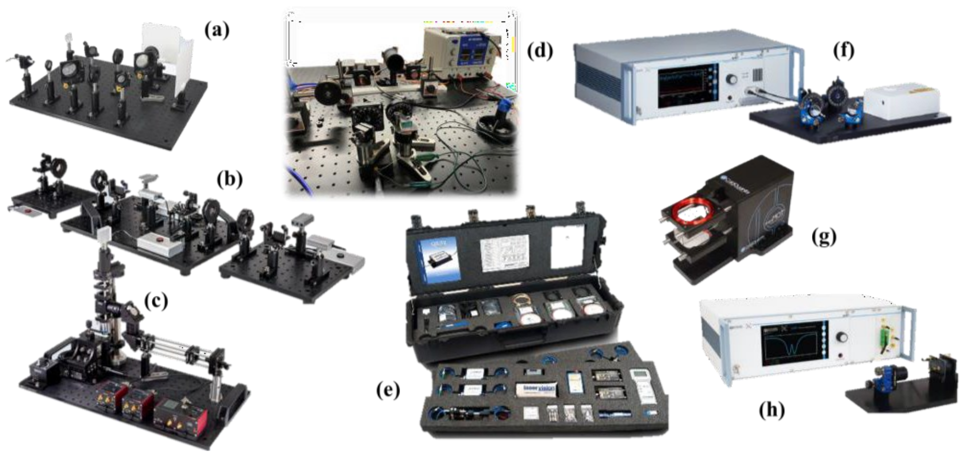

Figure 4. Educational equipment in the quantum laboratory at Indian River State College in Fort Pierce, Florida—(a) Michelson interferometer, (b) quasi-quantum cryptography, (c) optical tweezers, (d) organically-established quantum setup, (e) quantum kit with compact bi-photon source, (f) quantum entanglement demonstrator, (g) quantum diamond magnetometer, and (h) trapped ion system.

An essential segment of the EdQuantum curriculum is the hands-on training offered in the quantum laboratory at Indian River State College. The laboratory hosts an extensive collection of commercially available quantum educational equipment. This equipment can be separated into the following categories: (1) organically-established quantum experiments, (2) quasi-quantum educational kits with a lower power laser source, (3) fundamental quantum experiments with a compact bi-photon source, (4) quantum sensing equipment, and (5) trapped atom instrumentation.

<u>Organically-established quantum experiments.</u> These experiments are put together from the ground up by using individually-purchased optical components. Single and entangled photons are created through spontaneous parametric down-conversion using barium borate crystals. These experiments replicate similar experiments at Colgate University [12]. This approach provides the most affordable setup. Still, it requires significant time to set and align the system that an instructor may not have during the teaching process.

Quasi-quantum experiments. These experiments are performed by utilizing weak laser signals from low-power sources. Although these experiments are not entirely quantum, they provide a relatively affordable way of teaching quantum concepts through the interaction-free quantum experiment, a Michelson interferometer, and a quasi-quantum cryptograph kit.

Quantum experiments with a compact bi-photon source. A few commercially-available educational kits provide a compact solution for a single-photon and bi-photon source based on spontaneous parametric down-conversion. This solution is similar to organically-developed quantum experiments but with a source already aligned and packaged in a small footprint. The benefit of this solution is relatively easy setup that allows the instructor to start with quantum experimentation immediately. Some kits may be purchased with a motorized option that allows remote experimentation.

Quantum sensing experiments. These experiments are based on a quantum diamond magnetometer through which students are introduced to the concepts of quantum sensing. The system is based on an HPHT diamond with an ensemble of nitrogen vacancy (NV) centers. The NV centers can be excited by light in the visible spectrum. The excited state decays back to the ground state where the decay path depends on the electron spin of the NV centers. The electron spin can be read optically.

Trapped atom instrumentation. This compact system provides a compact solution to magneto-optic trapping of atoms used to introduce students to the process of laser cooling of atoms, the concepts of Bose-Einstein condensates, and the fundamentals of quantum matter.

Acknowledgments

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