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Inviting Millions Into the Era of Quantum Technologies

Now that the potential of quantum technologies is becoming clearer, the United States must work quickly to build a workforce that reflects the diverse perspectives of our society.

Quantum technologies involving sensing, networking, and computing are beginning to transform areas as diverse as health, geology, astrophysics, materials science, and finance. Building on decades of work in theoretical and experimental quantum physics, these emerging technologies have the potential to provide jobs to diverse communities and benefit American society and national security. But for every three current quantum technology job openings today, the United States has only one qualified candidate—and by 2025, McKinsey analysts predict, more than half of the country's quantum jobs will go unfilled. To realize the field's potential, the United States must begin developing a quantum information science and technology (QIST) workforce that can meet the demands of industry, academia, government, and national laboratories.

Employers are already searching for talent from a broad range of backgrounds. In their list of the top quantum computing jobs and careers, the *Quantum Insider* describes positions open to software and hardware engineers and physicists with PhDs—as well as roles for those with bachelor's degrees and programming knowledge. They also note that quantum-related openings for nonscientists in marketing, sales, and business development are increasingly common.

This workforce challenge should be met by a national effort to develop educational pathways for quantum technologies across high schools and community colleges, as well as in undergraduate and graduate settings. By applying lessons learned from previous advanced technology transitions, the United States can build an educational infrastructure to provide broader access to these new technologies, enabling workers' skills to advance along with the field. And giving millions of Americans access to quantum jobs at this early stage will put them in a position to positively guide the development of these technologies toward societal benefit.

As lead organizers for the Quantum Collaborative, we have been working to expand the quantum workforce since April 2022. Founded by Arizona State University in collaboration with more than 40 partners, this initiative integrates knowledge and work streams across academic institutions, industry, national laboratories, and others to mutually advance both research and education from kindergarten through postsecondary education. Through this experience, we have identified several opportunities to enhance the way resources are allocated to drive success. The most urgent of these opportunities is a need for funders and policymakers to act quickly to support the implementation and growth of quantum technology infrastructure for a range of learners.

Moving beyond physics

The National Quantum Initiative Act (NQI) of 2018 outlined a plan to coordinate research with funding of $1.2 billion in federal investments across multiple years. The NQI has continued, with the Biden administration allocating over $800 million in 2023. About three-quarters of this funding is assigned to quantum sensing, networking, and computing. In 2022, the National Science and Technology Council released a strategic plan for quantum workforce development, outlining four critical actions necessary to build a robust workforce while increasing accessibility and equity. Today, significant funding for education and workforce programs flows through the National Science Foundation (NSF). For example, the White House Office of Science and Technology Policy partnered with NSF to launch the National Q–12 Education Partnership. Both the US Department of Energy (DOE) and Laboratory for Physical Sciences, supported by the National Security Agency, have joined these workforce development efforts.

Many programs aim to promote an interdisciplinary workforce, but one of the headwinds they face is that emerging quantum technologies build on decades of theoretical development in quantum physics. This earlier work is now often called Quantum 1.0. In today's era of Quantum 2.0, engineers apply principles of quantum mechanics to create quantum technologies. Thus, the foundational expertise required for participating in quantum technologies is no longer purely physics—it's increasingly engineering, or a combination of engineering with physics and other fields. However, many academic programs and research initiatives remain firmly anchored to physics, which conflicts with the interdisciplinary nature of Quantum 2.0.

Today, the need for an interdisciplinary workforce can be seen clearly in quantum sensing, the most market-ready of the three Quantum 2.0 technology areas. Quantum sensing affords increased precision in detection and measurement—a valuable advance in fields such as medicine, materials science, geology, astrophysics, and navigation. Translating these new capabilities to applications requires skills represented across a range of positions, from the technician level all the way up to subject-matter experts; in user-facing roles such as product design; and in several domains of engineering tasked with developing solutions for these markets. Recognizing the many potential pathways for this technology, the Air Force Office of Science Research has a variety of special programs underway, and NSF recently funded 18 interdisciplinary research teams at universities across the nation to explore ways to develop useful quantum sensing capabilities.

Interdisciplinarity is also fundamental to the second emerging area, quantum networking, which builds on the principles of quantum entanglement to create information networks that are resistant to eavesdropping. Although this technology is in its early days, it is expected to transform many aspects of telecommunications, with significant research already occurring in the security space—including projects supported by the Department of Defense and the Defense Advanced Research Projects Agency. Soon, these capabilities will need to be integrated with existing technology, requiring collaboration across disciplines and among people of different skill levels. In the civilian sphere, DOE is leading funding for this work with support from NSF and programs organized by the National Institute of Standards and Technology. Many of today's efforts are rooted in the national laboratories, including Argonne, Brookhaven, Lawrence Berkeley, Oak Ridge, and the Fermi National Accelerator Laboratory, as well as at the Air Force Research Lab.

Quantum computing, the third emerging technology, is also profoundly interdisciplinary. The latest hardware platforms are maturing and promise breakthroughs in chemistry, financial analysis, biology, pharmaceutical and materials development, and complex optimization. Related and ongoing work over previous decades involving quantum simulators successfully delivered breakthroughs in materials science, nanotechnology, and other areas.

In contrast to the first two Quantum 2.0 technologies, today's advancements in quantum computing hardware platforms are heavily driven by industry. Corporations developing proprietary architectures include Google, Quantinuum, IBM, Microsoft, IonQ (spun out of the University of Maryland and Duke University), Infleqtion, and Rigetti.

Even though a very broad range of interdisciplinary learners across the country could be engaged with Quantum 2.0, most of today's training programs are situated in national laboratories, big corporations, and highly resourced universities. Thus, quantum technology research and infrastructure remain isolated from the broader universe of potential workers. For example, the NSF-funded Quantum Leap Challenge Institutes offered five-year, $25 million grants to develop interdisciplinary efforts to advance the frontiers of quantum technology. These grants have gone to the University of California, Berkeley, University of Illinois at Urbana-Champaign, University of Colorado at Boulder, University of Maryland, College Park, and University of Chicago—all among the country's top universities for quantum physics.

Today, large institutions with strong quantum physics departments can access resources through industry partnerships, large-scale federal awards, state investment, or other means. But these resources remain unavailable to many others, including smaller institutions that must prioritize essential needs, such as access to reliable internet connectivity on campus.

Breaking with past patterns to democratize access

The developing research ecosystem for Quantum 2.0 is repeating old dysfunctional patterns found, for instance, among the early years of supercomputing in the United States, when access to advanced computing resources was limited to institutions and faculty with strong ties to industry giants such as IBM and Cray (a supercomputer manufacturer) or to national laboratories. In the 1960s, NSF began to fund advanced computational infrastructure on college campuses. Still, it was not until the late 1980s that NSF started funding programs designed to broadly democratize access to advanced computing infrastructure, ultimately leading to the successful TeraGrid and Extreme Science and Engineering Discovery Environment (XSEDE) programs—both of which made these computing resources accessible to a wide range of researchers and students, including those not directly funded by NSF.

Democratizing access to powerful computing systems led to wider impact and vastly increased rates of discovery. TeraGrid and XSEDE enabled over 28,000 scientific publications from across the United States. ACCESS (Advanced Cyberinfrastructure Coordination Ecosystem: Services and Support), the latest program and successor to XSEDE, ensures diverse learners and researchers across the country can use advanced computational infrastructure. For example, Purdue University's Anvil supercomputer, funded by NSF and available through ACCESS, serves thousands of researchers around the country. Beyond providing training and infrastructure, Anvil funds outreach specialists who engage nontraditional domains, K–12 organizations, and minority serving institutions (MSIs). NSF has also funded the Minority Serving Cyberinfrastructure Consortium (MS-CC), where MSI representatives determine strategic technical priorities for their communities.

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To further broaden access to quantum technologies, models like ACCESS and MS-CC can be used to bring quantum computing resources to a diversity of learners across the country. Today's nonquantum supercomputing systems can immediately be outfitted with openly available simulation software to support learners in high schools, community colleges, and universities using any of the robust, open-source software solutions developed by industry—IBM's QisKit, Quantinuum's TKET, Google's Cirq, and NVIDIA's cuQuantum, to name a few—enabling millions to gain hands-on experience. These same platforms could support a variety of research activities. NSF is well-positioned to address this through programs such as Campus Cyberinfrastructure, Cyberinfrastructure for Sustained Scientific Innovation, or Advanced Computing Systems & Services.

We are hardly the first to suggest the need to expand access to quantum resources. Speaking before the House Committee on Science, Space, and Technology in June 2023, National Quantum Coordination Office director Charles Tahan said, "We need to get quantum computing test beds that students can learn in at a thousand schools, not 20 schools," adding that training and recruiting talent are "the most important actions" that can be taken to strengthen US leadership in this field.

Seizing opportunities to fulfill quantum's promise

As quantum technologies advance, collaboration among all tiers and types of learning institutions will be vital to ensure students, technicians, and others can find or develop pathways that allow them to continuously gain skills and develop satisfying careers. We see specific opportunities in Quantum 2.0 learning and professional development that could be quickly seized to promote US leadership in these technologies while accomplishing important domestic goals.

First, metrics are needed so that the public and policymakers can track progress against the goals of the National Quantum Initiative. Identifying a baseline sense of where quantum technology programs, infrastructure, and experts are today will allow for a more accurate survey of the landscape and inform strategic placements of new investments. The National Science and Technology Council's plan for quantum workforce development described the frustration of not having this knowledge: "At this time, there is no singular, comprehensive source of data that provides definitive, quantitative information regarding the QIST workforce landscape. Based on the information that is available, there appears to be a talent shortage at all levels."

Decisionmakers also need good data on what the market is calling for. Many quantum technology workforce programs currently target early-career PhD researchers or graduate students. However, a 2022 survey of 57 companies conducted by the Quantum Economic Development Consortium found that in addition to quantum expertise, some quantum technology employers require skills within the business, software, and hardware sectors. A follow-up survey revealed the need for technicians with certificate-level training who can step into roles in systems administration and quality management. More than 80% of industry respondents indicated interest in upskilling current employees with quantum skills, and over 60% indicated willingness to invest time to codevelop technician programs with community college and university partners. Nearly all said they need technicians now and in the coming years.

Given this specific need for technicians, we see a real opportunity to direct quantum education resources toward community colleges. These institutions serve almost half of undergraduate students in the country, and many community college engineering graduates subsequently transfer into four-year programs. However, despite this opportunity, information about quantum opportunities for students at this educational stage is scarce.

Another model for reaching significant numbers of learners is the IBM-HBCU Quantum Center at Howard University. By connecting 22 colleges and universities, from Maryland to Texas and across multiple research areas, the initiative aims to empower historically Black colleges and universities to lead in advancing quantum technologies. Similar initiatives could enable MSIs to connect with other institutions and develop expertise and infrastructure across geographic areas.

A vital opportunity to introduce millions of students to the principles of quantum technologies is found across high schools, liberal arts colleges, and among continuing learners—including veterans, who bring important tacit knowledge and interdisciplinary experiences. Here, there is a successful model that comes from outside traditional education. A nonprofit initiative called Qubit by Qubit has delivered an introductory course on quantum computing to 20,000 students in high school and beyond. Attendees learn about quantum technology applications and hardware while gaining quantum coding skills. With the only prerequisite being high school geometry, Qubit by Qubit has found that students with limited scientific or technical backgrounds are capable of developing foundational skills in quantum technologies. Further, many students expressed interest in pursuing additional studies or careers in quantum, signaling the importance of early exposure. The Qubit by Qubit program demonstrates a potential role for nontraditional education programs in building social awareness of—and foundational skills in—quantum technologies.

One federal program designed to address quantum technology workforce gaps while increasing diversity is NSF's Expanding Capacity in Quantum Information Science and Engineering program, introduced in 2022. Arizona State University became an early award recipient for the program when it applied for funding both to conduct research and to create supplemental Quantum 2.0 pathway programs for engineers. Our collaborators among the Alliance of Hispanic Serving Research Universities were unable to follow suit because program requirements were changed after launch to render universities classified as R1—doctorate-granting universities with "very high research activity"—ineligible as lead institutions. This meant colleagues at the University of Texas at San Antonio, an exemplar in cybersecurity workforce development that recently achieved R1 status, and the University of Central Florida, which supports more than 65,000 learners, became ineligible to lead proposals when it was too late to build partnerships with non-R1 institutions as leads. Future iterations of this and other programs should find ways to balance a diverse portfolio of lead institutions and the learners they represent.

Another promising program is DOE's Reaching a New Energy Sciences Workforce, which promotes training and research experiences for members of underrepresented communities by opening up access to resources at national laboratories and other facilities managed by the DOE Office of Science. This model enables smaller organizations to get direct access without going through peer institutions. Although limited to the DOE community and small in funding support, this structure could be expanded to diversify the quantum technology community in support of this agency's focus on quantum networking and among other NQI interest areas.

The jobs ahead

A few weeks ago, we visited the headquarters of a Quantum 2.0 company that the Quantum Collaborative partners with. In the past year, the company built a wing nearly the size of a football field intended to house dozens of electrical engineers. So far, only a few have been hired. During our visit we walked past yard after yard of empty workbenches as our liaison explained that the lack of electrical, mechanical, systems, and other engineers who understand the high-level concepts of quantum is causing him deep concern. Like us, he dreams of an army of technicians who are tech-savvy, interested in quantum, and willing to take on roles such as quality control operators and control center managers.

Now that the potential of quantum technology across sensing, networking, and computing is becoming clearer, it is time to work quickly to build the workforce that will design and deliver solutions that benefit and protect the nation. And we believe that deeper, fundamental issues about the development of the technology itself are at stake if the United States misses this opportunity to build a quantum workforce that mirrors the diversity of its society.

Failure to bring diverse perspectives into the development of artificial intelligence is one of the factors that led to the creation of biased solutions in medicine, health, law enforcement, and other vital areas. Deliberately building pathways to welcome all sectors of the population to participate in quantum technology development can help mitigate technological harms. In addition, recruiting a diverse workforce leads to innovations that serve a broader set of interests, which can translate to wider acceptance and adoption of these technologies as they emerge. Broadening access to education is one way to ensure quantum technologies are far more accessible, less likely to be misused or misunderstood, and more likely to be applied and adopted in a greater diversity of contexts.

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