The U.S. Approach to Quantum Policy

By Hodan Omaar | October 10, 2023

The government's interest in quantum technologies dates back at least to the mid-1990s, when the National Institute of Standards and Technology (NIST), Department of Defense (DOD), and National Science Foundation (NSF) held their first workshops on the topic.[1] NSF described the field of quantum information science in a 1999 workshop as "a new field of science and technology, combining and drawing on the disciplines of physical science, mathematics, computer science, and engineering. Its aim is to understand how certain fundamental laws of physics discovered earlier in this century can be harnessed to dramatically improve the acquisition, transmission, and processing of information."[2] In the nearly 25 years since NSF's first workshop, quantum information science has advanced and its potential to drive major advances in computing power, secure communication, and scientific discovery have become more apparent. The U.S. government has rightly recognized that it needs to play an active role in ensuring the nation remains competitive in this critical field.

OVERVIEW OF CURRENT U.S. POLICY APPROACH

Quantum information science (QIS) is an umbrella term encompassing several different technologies. In this report, "QIS" or "quantum" encompasses the following five technologies:

- **Quantum sensing and metrology**, which refers to the use of quantum mechanics to enhance sensors and measurement science.

- **Quantum computing**, which refers to the development of computers that use quantum mechanics to perform calculations exponentially faster than classical computers.

- **Quantum networking**, which refers to the development of secure communication protocols that use the principles of quantum mechanics to ensure the confidentiality and integrity of transmitted information.

- **QIS for advancing fundamental science**, which refers to using quantum devices and QIS theory to expand fundamental knowledge in other disciplines; for example, to improve understanding of biology, chemistry, and energy science.

- **Quantum technology**, which catalogs several topics including using quantum technologies to create practical applications; creating the necessary infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and minimizing the risks associated with quantum technologies, such as developing post-quantum cryptography to protect sensitive information.[3]

There has been important action from both the executive branch and the legislative branch in recent years to shape QIS policy.

On the executive side, the White House has issued two seminal reports articulating a national strategic approach to QIS through the National Science and Technology Council (NSTC), which is the principal body through which the executive branch coordinates quantum policy across the diverse entities that make up the federal research and development (R&D) enterprise. NSTC published its first report titled *Advancing Quantum Information Science: National Challenges and Opportunities* in July 2016 under President Obama.[4] This report outlined three principles to help guide an "all-of-government approach to QIS," which were to maintain stable and sustained core programs that could be enhanced as new opportunities appear and restructured as impediments evolve; invest strategically in targeted, time-limited programs to achieve concrete, measurable objectives; and closely monitor the QIS field to evaluate the outcome of federal QIS investments and quickly adapt programs to take advantage of technical breakthroughs as they are made.[5]

NSTC released its second report, *National Strategic Overview for Quantum Information Science,* in September 2018 under President Trump, and this report identified six policy opportunities and priorities for federal quantum investments:

- Choosing a science-first approach to QIS

- Creating a quantum-smart workforce for tomorrow

- Deepening engagement with quantum industry
- Providing critical infrastructure
- Maintaining national security and economic growth
- Advancing international cooperation[6]

On the legislative side, the most significant piece of legislation related to quantum to date has been the National Quantum Initiative Act (NQIA), a bill signed into federal law in December 2018 that was designed to accelerate and advance quantum science and technology in the United States. Essentially, the NQIA created a framework for quantum R&D and authorized just over $1.2 billion in funding over five years (fiscal years 2019 to 2023) for a variety of initiatives, allocated primarily across the three agencies that have historically been heavily involved in QIS R&D: NIST, NSF, and the Department of Energy (DOE). Some of the NQIA's key components include authorizing these agencies to strengthen QIS programs and research centers; establishing a new federal agency called the National Quantum Coordination Office (NQCO), housed under the Office of Science and Technology Policy (OSTP), and tasking it with coordinating QIS activities across the federal government, industry, and academia; and establishing a new federal advisory committee called the National Quantum Initiative Advisory Committee (NQIAC), composed of experts from academia, industry, and government and tasking it with providing independent assessment of and recommendations for the NQIA program. The programs the NQIA authorize expired on September 30, 2023, and the bill needs to be reauthorized in order to continue U.S. leadership in this critical field.

The CHIPS and Science Act of 2022 amended the NQIA to authorize R&D in quantum networking infrastructure; instruct NIST to develop standards for quantum networking and communication; establish a DOE program to facilitate a competitive, merit-reviewed base process for access to U.S.-based quantum computing resources for research purposes; and require NSF to support the integration of QIS into the science, technology, engineering, and mathematics (STEM) curriculum at all education levels.[7] It also explicitly includes QIS in the new NSF directorate focused on emerging technologies, the Directorate for Technology, Innovation, and Partnerships (TIP).[8]

This rest of this report explores four broad policy areas the U.S. government uses to promote competitiveness in quantum. These are policies that support quantum R&D, strengthen the quantum workforce, build a quantum ecosystem, and collaborate with international partners.

This report also makes 10 recommendations across these policy areas to Congress:

1. Reauthorize the NQIA and appropriate at least $525 million per year (in addition to the CHIPS funding) for FY 2024 to FY 2028.

2. Fully fund the quantum user expansion for science and technology (QUEST) program authorized by the CHIPS and Science Act to improve researcher accessibility to U.S. quantum computing resources.

3. Establish a quantum infrastructure program within DOE to help meet the equipment needs of researchers as part of the reauthorization of the NQIA.

4. Fully fund the NSF Quantum Education Pilot Program authorized in the CHIPS and Science Act, which would allocate $32 million over the next five years to support the education of K-12 students and the training of teachers in the fundamental principles of QIS.

5. Direct NSF to collaborate with NIST to conduct a systematic study of quantum workforce needs, trends, and education capacity.

6. Authorize and fund a DOE-led training program that partners students studying toward bachelor's, master's, or Ph.D. degrees with DOE national labs for hands-on QIS experience.

7. Direct the Department of Commerce to work with the Quantum Economic Development Consortium (QED-C) to review the quantum supply chain and identify risks.

8. Direct and fund the recently established Directorate for TIP within NSF to establish quantum testbeds for use-inspired research.

9. Direct DOE to establish and lead a program that invites allied nations to co-invest in quantum moonshots.

10. Direct NIST to prioritize promoting U.S. participation, particularly from U.S. industry stakeholders, in international standards fora in the reauthorization of the NQIA.

SUPPORTING QUANTUM RESEARCH & DEVELOPMENT

While civilian, defense, and intelligence agencies have a long history of investing in quantum R&D, the government has taken important steps recently to accelerate, strengthen, and coordinate federal quantum R&D investments with the NQIA and CHIPS and Science Act.[9] Three of the most important government actions supporting QIS R&D are in increasing QIS R&D funding, facilitating interdisciplinary research, and facilitating access to R&D resources.

Increasing QIS R&D Funding

The NQIA catalyzed a significant increase in federal funding for QIS R&D, roughly doubling federal funding between FY 2019 and FY 2023. It is important to note that while the NQIA sets funding targets and priorities for QIS R&D across various federal agencies, it does not guarantee specific funding amounts. The president and Congress set nondefense quantum R&D priorities and funding for each federal agency through an annual fiscal year budget, with defense spending set through a separate bill called the National Defense Authorization Act.

Figure 1 shows U.S. R&D budgets for QIS since the inception of the NQIA, with agencies reporting actual budget expenditures for quantum R&D of $449 million in FY 2019, $672 million in FY 2020, and $855 million in FY 2021, followed by $918 million of enacted budget authority for quantum R&D in FY 2022 and a requested budget authority of $844 million for quantum R&D in FY 2023. [10] The portion of each bar in figure 1 marked "NQI" identifies funding allocated for NQIA-authorized activities, meaning it is additional funding on top of the budgets for baseline QIS R&D activities.

Figure 1: U.S. Quantum Information Science R&D budgets after National Quantum Initiative Act was enacted[11]

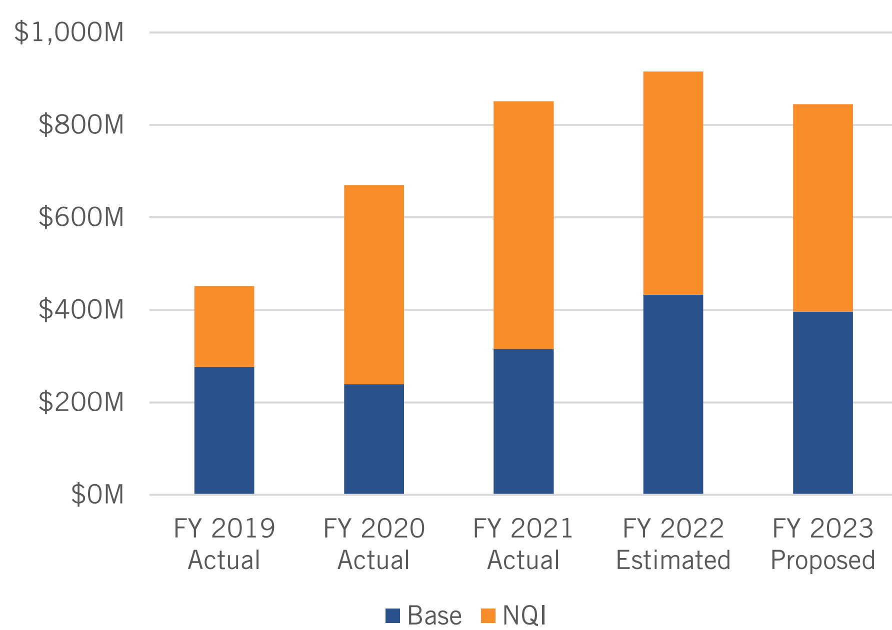
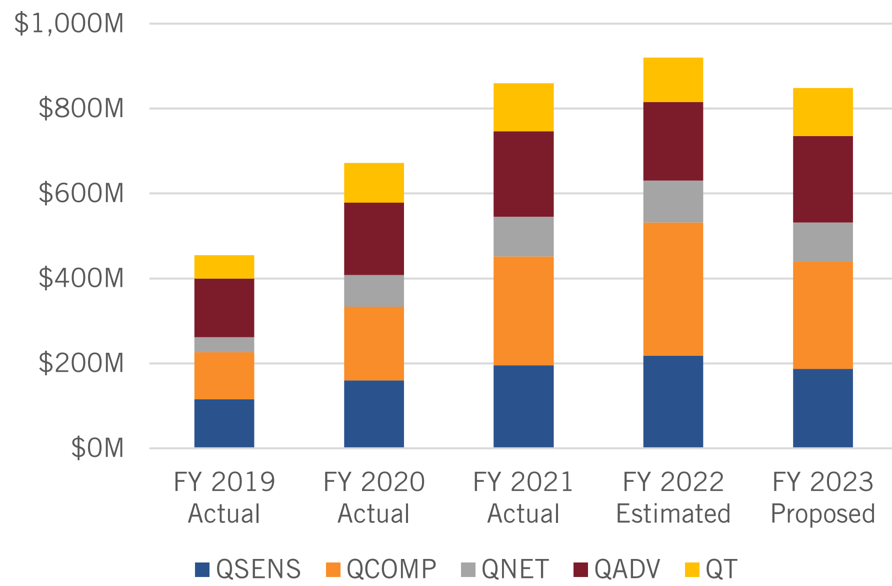


Figure 2 shows that the government has increased and sustained funding across all five program component areas that were classified in the *National Strategic Overview for QIS*, namely quantum sensing and metrology (QSENS), quantum computing (QCOMP), quantum networking (QNET), quantum advancements (QADV), and quantum technology (QT).

Figure 2: U.S. Quantum Information Science R&D by program component area[12]



There is widespread consensus that increased funding is necessary. Indeed, the NQIAC discussed its recommendations to Congress on how it should fund the next iteration of the National Quantum Initiative and one of its central recommendations was that sustained and increased funding "will be necessary for our nation to win the race to realize the benefits of QIS."[13]

This is true. Quantum technologies are still in the very early stages and the road to maturity and diffusion is long. The first step in the innovation process is what Princeton Professor Donald Stokes called "Pasteur's quadrant" research—basic research directed at a specific challenge or problem.[14] This type of research provides foundational, generic knowledge that industry can draw on for ideas and innovation. The problem is the private sector is not sufficiently incentivized to conduct fundamental research because it is almost never able to capture all the spillover benefits of initial investments, or capture these benefits fast enough, to justify investing at the same level as the government. This is especially true in the case of basic research, which is costlier and riskier than applied R&D.[15] Also, the private sector tends to narrowly focus its research on only the fields that are commercially relevant and economically beneficial, rather than on all those that might advance the public good. Federal funding for QIS R&D is therefore critical to ensure the effective development of new knowledge, techniques, and technologies.

Increased and sustained funding is particularly necessary to stay competitive because several other countries are investing in QIS R&D, some funding QIS far more than the United States is. The United Kingdom, for example, is launching a 10-year program as part of its National Quantum Strategy, which promises to invest £2.5 billion ($3.1 billion) in quantum R&D starting in 2024 with the aim of attracting an additional £1 billion ($1.3 billion) of private investment.[16] And the EU is investing public funding for quantum computing that is almost four times that of the United States, while China's is almost eight times that of the United States.[17]

The question becomes, How much funding is enough to accelerate U.S. QIS innovation and keep the nation competitive? That is difficult to answer in part because, while the government's efforts to increase QIS R&D funding through the NQIA are easily quantifiable, the benefits of these efforts are more difficult to quantitatively translate because there exist few consistent, comprehensive measures of how much U.S. QIS research has changed over time. It might be the case that the NQIAC has this data as part of its assessment of the NQI program, but it has not publicly released this information. However, in its written comments to the NQIAC in March 2023, the Energy Sciences Coalition, a broad-based coalition of over 100 organizations representing scientists, engineers, and mathematicians in universities and industry and national laboratories, recommended "at least $675 million each year over five years from FY 2024 through FY 2028."[18]

While there are reasons to be hopeful that there will be substantial funding for quantum, there are also reasons to be less optimistic. On the positive side, Congress has already authorized significant amounts of quantum funding through the recently passed CHIPS and Science Act of 2022. Although no funds have been appropriated, the CHIPS and Science Act is authorizing legislation that sets funding targets that aim to energize American innovation across a variety of industries—one of which is quantum. It directly authorizes new investments in core quantum research programs, such as $500 million toward an R&D program for quantum networking infrastructure, but it also significantly increases investments in many other critical industries that will feed into quantum applications, such as $2 billion for a DOD-led microelectronics R&D program that will be pay huge dividends to the development of quantum systems that rely on microelectronic components.

Unfortunately, despite many political leaders paying lip service to the act's goal of bolstering American competitiveness in key innovation industries, the CHIPS and Science Act is not getting the funding it needs. Neither the Biden administration's FY 2024 budget request nor the federal government's omnibus spending bill for the 2023 fiscal year have met the funding target set by CHIPS. The administration's budget request falls short of agency targets by more than $5 billion, while the omnibus funding is nearly $3 billion short of the authorized targets for NSF, DOE's Office of Science, and NIST.[19]

What's more, funding for CHIPS and the reauthorization of the NQIA look to be tight given recent battles over lowering overall federal spending.[20] As a member of the House Science, Space, and Technology Committee working on the reauthorization noted in a 2023 Center for Data Innovation panel, "There are different parameters in this Congress than there were last year in the 116th [Congress] … I don't think that we're going to be seeing a CHIPS-like program."[21] However, as another member on the committee put it, "It is essential that the 'Science' part of CHIPS and Science is appropriated money and that will pay huge dividends in quantum information science, in both basic and applied research."[22]

Facilitating Interdisciplinary Research

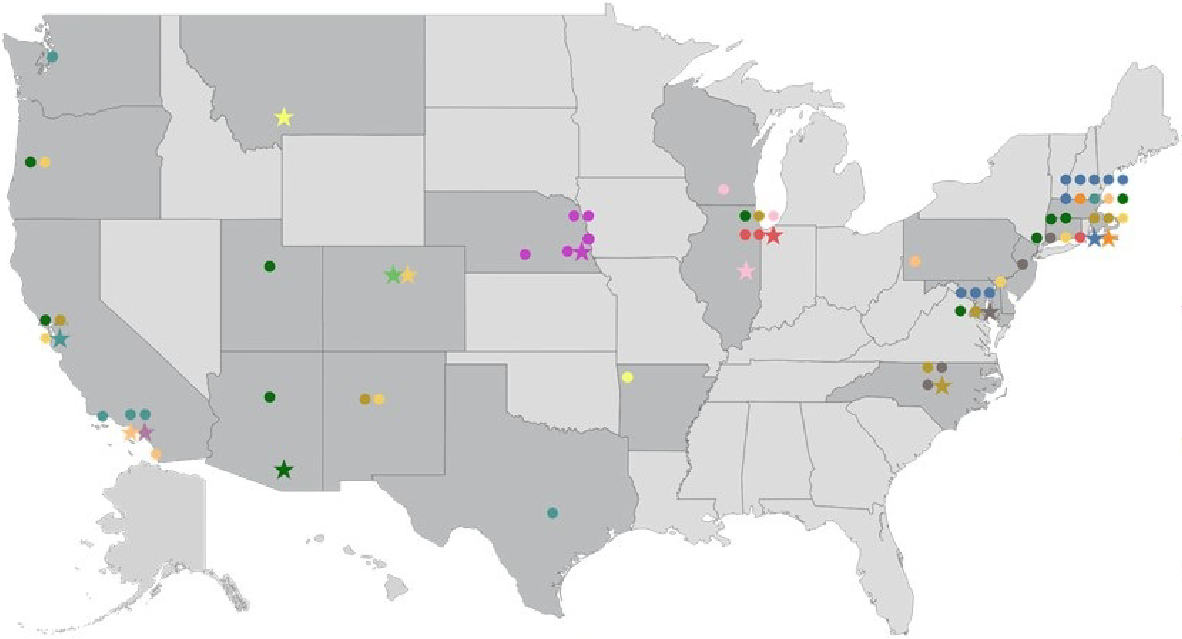
NSF presciently identified in its workshop back in 1999 that quantum research is profoundly interdisciplinary and advancements in the field would require "the combined effort of people with expertise in a wide variety of disciplines, including mathematics, computer science and information theory, theoretical and experimental physics, chemistry, materials science, and engineering."[23] Consider a research project investigating the development of a scalable, fault-tolerant quantum communication system. Developing a system that can operate in the presence of noise and other disturbances requires expertise in quantum communication protocols, computer algorithms, hardware design, and experimental physics.

Unfortunately, research institutes in the United States have not historically collaborated on quantum research across disciplinary boundaries very effectively. A 2018 report on quantum from the Congressional Research Service, a public policy research institute of Congress, found that "federal departments, and even agencies and offices within a department, have sponsored R&D at universities in different disciplines to address unique federal mission requirements. As a result, coordination and collaboration among university researchers is difficult."[24]

Both NSF and DOE are working to surmount these institutional barriers by supporting the establishment of interdisciplinary research centers, though they have taken different approaches that reflect their different missions and funding priorities. NSF is focused on facilitating faculty collaboration across departmental boundaries at university-based centers and institutes. As of March 2023, the agency had funded five Quantum Leap Challenge Institutes, which are large-scale interdisciplinary research institutes led by universities to advance specific frontiers of QIS and engineering. For instance, the University of Maryland is leading one of the five institutes, the Quantum Leap Challenge Institute for Robust Quantum Simulation, which is focused on building systems that can robustly simulate the behavior of quantum systems.[25] This institute brings together researchers from five universities: Duke, Princeton, North Carolina State University, Yale, and the University of Maryland.

Figure 3 shows that NSF is not only funding research centers focused on the broader study of quantum science and technology but also funding several quantum foundries, which are specialized research centers that focus on developing and manufacturing the materials quantum technologies need, such as qubits and quantum sensors.

Figure 3: NSF's center-scale investments in QIS research centers[26]



NSF Engineering Research Center for Quantum Networks (CQN) (Award -1941583)
University of Arizona
Brigham Young University
University of Massachusetts Amherst
Howard University
Massachusetts Institute of Technology
Northern Arizona University
Stanford University
University of Chicago
Harvard University
University of Oregon Eugene
Yale University

RII Track-1: Emergent Quantum Materials and Technologies (EQUATE) (Award -2044049)
University of Nebraska
Creighton University
Nebraska Indian Community College
University of Nebraska at Omaha
Little Priest Tribal College
University of Nebraska at Kearney
University of Nebraska-Lincoln

QLCI-CI: NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States (Award -2016244)
University of Colorado at Boulder
Harvard University
Massachusetts Institute of Technology
Stanford University
University of Delaware
University of New Mexico
University of Oregon Eugene

QLCI-CI: NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks (Award -2016136)
University of Illinois at Urbana-Champaign
University of Chicago
University of Wisconsin-Madison

Center for Integrated Quantum Materials (Award -1231319)
Harvard University
Bunker Hill Community College
Gallaudet University
The Learning Center for the Deaf
Massachusetts Institute of Technology
Prince Georges Community College
Museum of Science
Wellesley College
Howard University
Mount Holyoke College

The Institute for Quantum Information and Matter: Advancing the Entanglement Frontier (Award -1733907)
California Institute of Technology

JILA PFC: Measurement, Manipulation, and Meaning at the Quantum Frontier (Award -1734006)
University of Colorado at Boulder

Center for Ultracold Atoms (Award -1734011)
Massachusetts Institute of Technology
Harvard University

PFCQC: STAQ: Software-Tailored Architecture for Quantum co-design (Award -1818914)
Duke University
Massachusetts Institute of Technology
North Carolina State University
University of Maryland, College Park
Tufts University
University of Chicago
University of New Mexico
University of California-Berkeley

Enabling Quantum Leap: Q-AMASE-i: Quantum Foundry at UCSB (Award -1906325)
University of California-Santa Barbara
Boston University
University of California-San Diego
University of Pittsburgh

Enabling Quantum Leap: Q-AMASE-i: MonArk Quantum Foundry: Rapidly Incubating Translational Advances in QISE with a 2D-Quantum Materials Pipeline (2D-QMaP) (Award -1906383)
Montana State University
University of Arkansas

QLCI-CI: NSF Quantum Leap Challenge Institute for Present and Future Quantum Computing (Award -2016245)
University of California-Berkeley
California Institute of Technology
Massachusetts Institute of Technology
University of California-Los Angeles
University of California-Santa Barbara
University of Texas at Austin
University of Washington

QLCI-CI: NSF Quantum Leap Challenge Institute for Quantum Sensing in Biophysics and Bioengineering (Award -2121044)
University of Chicago
Chicago State University
Harvard University
University of Illinois at Chicago

QLCI-CI: NSF Quantum Leap Challenge Institute for Robust Quantum Simulation (Award -2120757)
University of Maryland, College Park
Duke University
North Carolina State University
Princeton University
Yale University

On the other hand, DOE has built interdisciplinary quantum research centers at its own national laboratories, where it can leverage its existing infrastructure and expertise to conduct cutting-edge QIS research. It has established five national QIS research centers:

- Co-design Center for Quantum Advantage, led by Brookhaven National Laboratory, focused on building the tools necessary to create fault-tolerant quantum computer systems
- Q-NEXT, led by Argonne National Laboratory, focused on how to reliably control, store, and transmit quantum information across distances
- Quantum Science Center, led by Oak Ridge National Laboratory, focused on advancing the science of quantum materials, sensors, and algorithms
- Quantum Systems Accelerator, led by Lawrence Berkeley National Laboratory, focused on developing a range of scalable quantum systems
- Superconducting Quantum Materials and Systems Center, led by Fermi National Accelerator Laboratory, focused on developing superconducting materials and devices for next-generation quantum computers

The NQIAC, as part of its assessment of the National Quantum Initiative, has evaluated progress in quantum collaborations and partnerships and found that overall, collaboration across centers is developing well. However, one issue hindering progress is the administrative burden on academic researchers. This problem is not new or specific to quantum research centers; there have been several reports over the last decade that indicate federal requirements imposed on research universities are excessive, impeding the efficiency and productivity of university research.[27] The NQIAC has found that these problems are impacting NSF center collaborations for quantum research and are getting worse over time, as well as limiting industry participation.[28] The committee's recommendations to Congress include that Congress should augment NSF center funding to support professional administrative staff and that it should support efforts to homogenize the forms and agreements that permit these collaborations.[29]

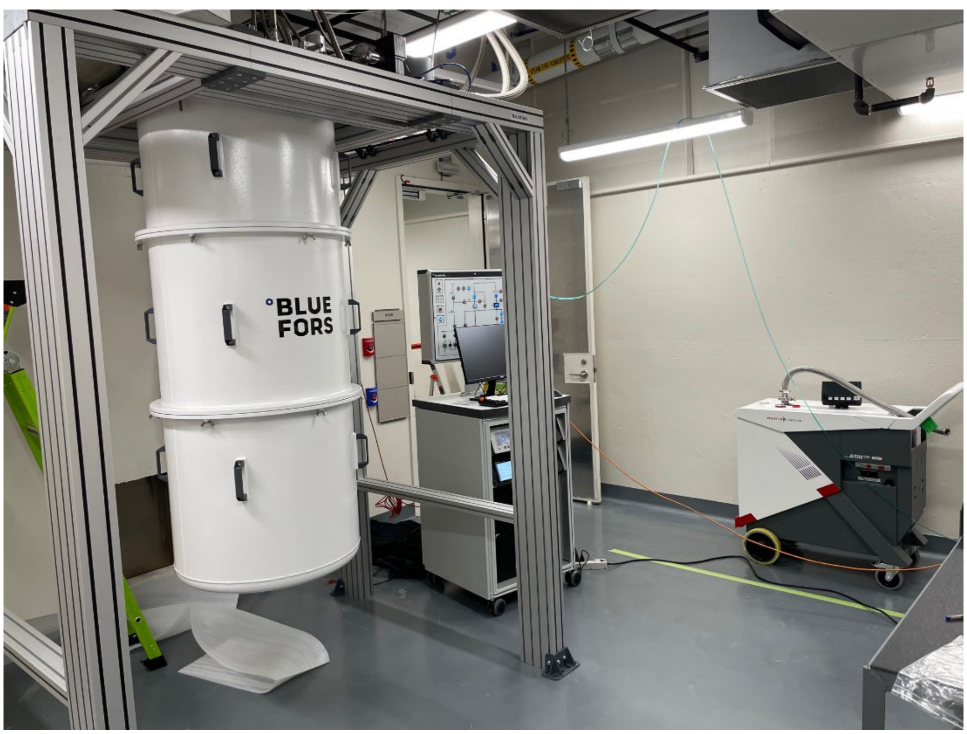
Facilitating Access to Quantum R&D Facilities

An important component of R&D leadership is the availability of world-class research facilities both at universities and at national labs. There are several types of research facilities any country needs to advance QIS, but perhaps three of the most important types are quantum user facilities, quantum foundries, and quantum testbeds.

A quantum user facility is a research facility that provides access to advanced quantum systems, such as quantum computers, for researchers and other users who may not have the resources or expertise to build or operate their own. Because user facilities are typically places where students, postdocs, and researchers go to use tools, they are uniquely positioned to support workforce development in ways that other R&D facilities might not. The Quantum Computing User Program at DOE's Oak Ridge National Laboratory, which provides access to state-of-the-art quantum computing resources, is an example of such a facility.

A quantum foundry is a facility or organization that specializes in developing and producing materials for quantum devices and systems, such as qubits, which are the basic building blocks of quantum computers. NSF funds quantum foundries at universities, such as the quantum foundry hosted at the University of California, Santa Barbara and the MonArk quantum foundry jointly led by Montana State University and the University of Arkansas.[30] DOE also funds and hosts quantum foundries, such as the Argonne Quantum Foundry, which is a 6,000-square-foot facility focused on developing scalable semiconductor quantum systems located at Argonne national laboratory.

Figure 4: A dilution refrigerator, which creates the ideal environment for qubit performance, at Argonne Quantum Foundry



A quantum testbed is a platform or system that is used for testing and experimenting with quantum computing hardware and software. These testbeds can include actual quantum computers, as well as simulation tools that allow researchers to simulate the behavior of quantum systems.

Testbeds are typically used to develop and refine quantum algorithms, software, and applications, and to test the performance of different types of quantum hardware.

The United States was once unique in providing world-leading research facilities to its researchers, but that is no longer the case. In fact, today, the United States lags behind other countries. DOE published a report in 2021 investigating how countries around the world are investing in constructing and upgrading research facilities for several critical fields, one of which was QIS, and found:

> While facilities in the U.S. set the pace technically, demand for access to them far exceeds their current capacity; access to comparable facilities is more extensive in other countries, especially in Europe. Additionally, supporting resources such as the number of staff scientists available to assist both university and industrial users of these complex facilities are more extensive outside the U.S.[31]

The NQIAC subcommittee on science and infrastructure reiterated these findings in its own evaluation of the status of research facilities. However, the committee noted that U.S. private sector research facilities surpass those of other nations and the nation should leverage this advantage.

The QUEST program authorized by the CHIPS and Science Act seeks to do just that. The bill is authorized at $165.8 million over five years and tasks DOE with working to improve accessibility to U.S. quantum computing resources, including private sector resources, for U.S.-based researchers and laboratories through a transparent, merit-review application process.

Recommendations

- **Congress should reauthorize the NQIA and appropriate at least $525 million per year (in addition to the CHIPS funding) for FY 2024 to FY 2028.** To ensure U.S. leadership in quantum, Congress should fund all the activities in the NQIA at the authorized level.

- **Congress should fully fund the QUEST program authorized by the CHIPS and Science Act to improve researcher accessibility to U.S. quantum computing resources.** The CHIPS and Science Act authorizes the largest publicly funded R&D program in U.S. history.[32] Funding for QIS is included in the “Science” part of the CHIPS and Science Act, while the CHIPS part provides for American semiconductor R&D. Unfortunately, government appropriations as they currently stand have fallen short of the targets set forth in the Act and have focused predominantly on the CHIPS portion. To properly drive quantum innovation, Congress should sufficiently fund the “Science” portion of the Act and, in particular, should fund the QUEST program.

- **Congress should establish a quantum infrastructure program within the DOE to help meet the equipment needs of researchers as part of the reauthorization of the NQIA.** Currently, there is no specialized program or funding source dedicated to meeting the distinct infrastructure requirements of quantum researchers and developers, and the NQIA so far has not sufficiently focused on supply chain needs and manufacturing capabilities. Creating a DOE-led program as part of the reauthorization could address this gap and should focus on establishing quantum foundries, specialized equipment, and laboratory facilities. The program should be authorized for at least $300 million over five years.

STRENGTHENING THE QUANTUM WORKFORCE

U.S. policy related to talent covers QIS education at the K-12 and higher education level, workforce training for the existing quantum workforce, and immigration policies to attract and retain foreign talent.

Quantum Education

Primary and Secondary Education

Quantum education at the K-12 level is just getting started. In the United States, the responsibility for primary and secondary education, including school financing, teaching credentials, and curricula fall on the states, but the federal government recognizes that it has a role to play in supporting their efforts to ensure the nation has a skilled quantum workforce.

At this stage, the focus of federal programs for K-12 quantum education is outreach and engagement, meaning introducing concepts of quantum technologies and science to students in middle and high school. OSTP and NSF joined forces in August 2020 to create the National Q-12 Education Partnership between the federal government, industry, professional societies, and the education community to provide a foundation for classroom and curricula materials.[33] Resources it has created include frameworks to help educators integrate QIS into STEM lessons and curricula such as those used in chemistry, physics, and computer science (CS) classes, as well as a repository of useful tools such as textbooks, lecture notes, and online courses for quantum-related education.[34]

However, one of the disadvantages of the decentralized U.S. approach to education is that it can lead to disparities in the depth and scope of integration efforts. Consider the integration of QIS into CS courses, which the national QIS partnership identifies as one of the most promising potential avenues for introducing students to QIS concepts.[35] Only 53 percent of U.S. high schools offer foundational CS and only 27 of the 50 states and District of Columbia require all high schools to offer CS.[36] Moreover, an NSF-funded study in 2018 found geographic disparities in where CS is taught, with schools in the West (44 percent) and Northeast

(43 percent) more likely to offer CS courses than schools in the Midwest (30 percent) and South (24 percent).[37] These disparities may mean only a limited number of schools can effectively integrate QIS into CS in the first place.[38]

An alternative to the U.S. approach is a more centralized, national government-mandated approach to QIS integration in STEM subjects such as that of the Netherlands. The Netherlands has a long history of studying quantum physics—some of the early pioneers of the field were Dutch—but the country only recently started teaching quantum physics as part of the national curriculum.[39] For context, the Dutch education system, much like that of several other European countries, has several tracks that provide students with different levels of education and prepare them for different career paths. The most academically challenging of these tracks is VWO, or *voorbereidend wetenschappelijk onderwijs*, which is a six-year program that prepares students for academic education at a research university and accounts for approximately a fifth of Dutch high school students.[40] In 2014, the Minister of Education amended the national VWO curriculum to include quantum physics into the syllabus and made this topic a compulsory part of the final exam. Some of the learning outcomes of the new syllabus are relatively complex, requiring students be able to "describe quantum phenomena in terms of the confinement of a particle" and "describe the quantum tunnelling effect by means of a simple model and indicate how the probability of tunnelling depends on the mass of the particle and the height and width of the energy barrier."[41] This approach may not be realistic within the realities of the U.S. education system, but the U.S. government should recognize that other countries are working to adapt their education systems to prepare their own future quantum workforces and consider how it can best ensure domestic education is equitable and functions as effectively as possible.

Besides formal classroom teaching, there are several informal learning opportunities under development for teachers, students, and families. Several nonprofits, learning programs, and courses have sprung up to provide accessible and inclusive quantum education to high school students such as Qubit by Qubit, an initiative of the California-based nonprofit organization the Coding School, which runs quantum summer camps for students in middle and high school as well as a year-long course in quantum computing that students in more than 150 U.S. high schools have taken.[42] This course is accredited by the Western Association of Schools and Colleges, meaning students can earn high school credits for taking it, and is approved by the University of California as a college preparatory course.[43]

The private sector is also reinforcing QIS integration in schools through a number of different initiatives ranging from after-school programs to hackathons. IBM has launched the IBM Quantum Educators program, which provides educators with resources and support to teach quantum computing concepts and skills. Microsoft has also launched the Quantum Development Kit, which includes resources for educators to teach quantum computing concepts, as well as tutorials and examples for students to learn how to program quantum computers. Finally, Intel's Quantum Computing Education program provides resources and support to educators and students to help them learn about quantum computing and its potential applications. While there may not be comprehensive data on the exact amount for-profit companies are contributing to quantum education, such initiatives and programs demonstrate that there is a growing interest and investment in supporting quantum education.

Higher Education

Unlike U.S. high schools, where QIS-related STEM education is subpar, there are U.S. institutions of higher education that boast strong STEM programs and are increasingly integrating quantum courses, drawing students from around the world.

At the undergraduate level, very few universities offer specific QIS majors. Instead, QIS-related courses are usually taken as electives at the upper division of STEM bachelor's degrees and mostly cover fundamental concepts or offer a broad introduction to quantum information topics. The University of Colorado Boulder, for example, offers a quantum engineering minor in a broad range of disciplines, and the University of Mexico offers a 10-week summer undergraduate research program in quantum technologies.[44]

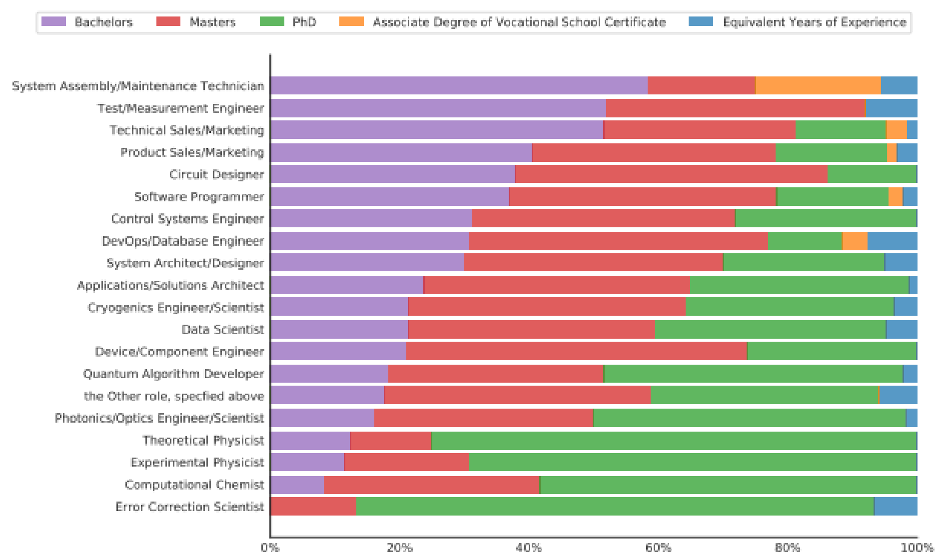
Specific quantum information-related tracks are more common at the master's level in disciplines such as physics, engineering, and computer science. Some schools have entire master's programs in quantum science, including University of California, Berkeley, Duke University, and Columbia University. Similarly, QIS-related tracks are often offered within existing Ph.D. programs such as in physics or computer engineering, though recently, Harvard University launched a Ph.D. program in quantum science and engineering that stands on its own.[45]

Ideally, colleges and universities would adapt their degree offerings to ensure students who want to study quantum-related fields can take the courses and learning opportunities they need in order to be prepared to thrive in future work. But in reality, universities face several challenges to reform.

From a financial perspective, quantum research and education require universities to invest in expensive equipment and facilities and hire qualified faculty to teach and develop curricula, all of which can be a significant financial burden. Budget restraints are particularly tight for publicly funded universities. More and more states in the last 10 years have changed how they give funding, from only considering how many students are enrolled to also rewarding universities for how many students complete their degrees.[46] A 2021 paper published in the *International Journal of Teaching and Learning in Higher Education* explains that "this model incentivizes maintaining student enrollment counts through large and required courses and may dissuade faculty from exploring innovative curricula that could reduce enrollments in courses within their own disciplines but ultimately better serve the needs of students."[47] Given a deepening enrollment crisis exacerbated by the COVID-19 pandemic, it is hard to imagine many public colleges and universities will have the bandwidth to effectively innovative with new quantum curricula without support.[48]

One thing that could help universities make more-informed decisions about how best to educate the future quantum workforce is knowing the type of quantum jobs available for their students and what skills and degrees are most relevant for those new jobs. Fortunately, a team of researchers led by DOE's Fermilab recently published a survey that assesses the degrees needed for different job roles in the U.S. quantum industry.[49] Figure 5 shows the different levels of education and qualifications 57 organizations said they would require for various jobs.

Figure 5: The distribution of degrees needed for different job roles in the quantum industry[50]



Two important takeaways emerge from the survey. First, there are a number of job opportunities in the quantum industry ranging from highly specific ones, such as quantum algorithm developer and error correction scientist, to broader jobs categories within the business, software, and hardware sectors. These broader jobs require a range of skills, most of which are not quantum related. Educators developing new curricula and degree programs should consider the balance between quantum-specific courses and more-general STEM courses. Second, companies are looking for a range of degree levels to fill new quantum positions, from bachelor's to master's to Ph.Ds., but a requirement for postgraduate degrees is more common. Therefore, universities may be wise to continue the trend of offering QIS-specific programs at the master's level and integrating singular classes or courses in existing programs at the bachelor level.

Workforce Training

The quantum field is creating more jobs in academia, industry, national labs, and government than can currently be filled, according to the *QIST Workforce Development National Strategic Plan* published in February 2022.[51] There are four workforce policies it identifies as key for the government: developing and maintaining an understanding of the workforce needs in the QIST ecosystem, introducing broader audiences to QIST through public outreach and educational materials, addressing QIST-specific gaps in professional education and training opportunities, and making careers in QIST and related fields more accessible and equitable.[52]

Several bodies, including the NQIAC and the QED-C, have echoed the urgency of the first action, understanding the workforce needs of the QIST ecosystem. But despite broad consensus that there is a skills gap problem, there does not seem to be a commonly agreed upon definition of what constitutes "QIS expertise" or the "QIS workforce." Without a common definition, it is difficult to truly understand the pervasiveness, scale, and concentration of skills misalignments. As figure 5 demonstrates, there are many types of expertise one can include in a measure of the QIS workforce, ranging from top error correction specialist to an entry-level technician who can assemble hardware. There are also many different domains of QIS expertise; a team wanting to use quantum computing to simulate chemical molecules would need expertise in quantum hardware, software, and algorithms, as well as an in-depth understanding of chemistry. Therefore, a first step would be for the government to clarify what constitutes the QIST workforce.

Attracting Foreign Quantum Talent

Attracting and securing highly skilled foreign-born talent plays a vital role in U.S. innovation and competitiveness in quantum. Consider that more than half of doctoral students who graduate with QIST-relevant backgrounds are non-U.S. citizens or non-permanent residents, or that many of the most important companies in the QIS ecosystem employ and are led by foreign-born workers.[53] Google's Quantum team, for instance, is led by Hartmut Neven, who was born in Germany, IBM's quantum computing team is led by Jay Gambetta, who was born in Australia, and California-based quantum computing company Rigetti Computing was founded by Canadian-born Chad Rigetti. Given the importance of foreign-born QIS workers to U.S. innovation success, the nation needs policies to strengthen and expand the immigration pipeline that allows highly trained QIS talent to innovate in the United States, including foreign STEM graduates of U.S. colleges and universities.

But while many competitor nations, including the United Kingdom, China, Canada, France, and Australia, have adopted flexible immigration policies to attract foreign talent in QIS and other technical fields, the U.S. immigration system has remained largely the same for the last 50 years. Its outmoded visa laws, as well as international competition for talent from other countries, are causing many international scientists and engineers to look outside the United States for education and employment. U.S. industry leaders note that foreign companies in countries with strong quantum backgrounds such as Canada, China, France, and the United Kingdom have been particularly adept at attracting the talent the United States has historically profited from.[54] Five years later, this trend does not seem much improved, as a February 2023 article in U.S.-based political newspaper *The Hill* indicates: "In the last decade, Canada has fostered an influx of new immigrant STEM workers and university students while the U.S. has done the opposite and is increasingly trending towards fewer immigrant STEM professionals working here."[55]

Recommendations

- **Congress should fully fund the NSF Quantum Education Pilot Program authorized in the CHIPS and Science Act, which would allocate $32 million to support the education of K-12 students and the training of teachers in the fundamental principles of QIS.** It would direct NSF to offer competitive, merit-based grants to institutions of higher education, nonprofits, and other organizations that would then partner with K-12 schools to develop and implement QIS curricula, incorporate QIS into the broader STEM curricula, offer opportunities for students to explore QIS higher education programs and career paths, and develop professional development and training programs in QIS for educators.

- **Congress should direct NSF to collaborate with NIST to conduct a systematic study of quantum workforce needs, trends, and education capacity.** There is little reliable data on the current and future workforce needs of the quantum industry or the capacity of U.S. institutions to effectively nurture quantum talent. This data will be key to inform ongoing investments in quantum education and workforce development programs. NSF should therefore lead a holistic study that elucidates the size and makeup of the supply and demand for talent, with well-defined methodologies for data collection. This study should be conducted and monitored once every two years to effectively assess trends, provide forecasts, and inform contingency strategies.

- **Congress should authorize and fund a DOE-led traineeship program that partners students studying toward bachelor's, master's, or Ph.D. degrees with DOE national labs for hands-on QIS experience.**

> This program should ensure it considers how to expand participation of underrepresented groups and institutions in QIS, including non-R1 academic institutions, Historically Black Colleges and Universities, and Minority Serving Institutions.

BUILDING A QUANTUM ECOSYSTEM

The United States has established a problem-focused, industry-led consortium called the QED-C whose primary focus is to enable and grow the quantum industry. The United States is not alone in creating such a body, as three other regions have similar consortiums: Japan's Quantum Strategic industry Alliance for Revolution, Quantum Industry Canada, and the European Quantum Industry Consortium. All are doing similar and important work, but QED-C has been critical for the United States in two particular areas: identifying supply chain dependencies and supporting commercialization.

Identifying Supply Chain Dependencies

Quantum computers appear to be the QIS technology with the most high-profile supply chain issues. In a 2022 report, the QED-C noted, "Based on a survey of quantum computing (QC) commercial entities spanning the QC ecosystem, there are significant concerns that there could be a serious QC-related supply chain disruption in the next few years. Potential choke points are widely dispersed across the supply chain spanning assured access to necessary raw materials to a steady supply of trained software experts."[56] The Government Accountability Office found similar results for QIS technologies generally, noting in a 2021 report, "The quantum technology supply chain is global and specialized. Given the complexity of the supply chain, if a single link in the chain is unavailable, that could cause technology development delays and other setbacks."[57]

In some instances, the United States is reliant on its allies. For example, Finland and the United Kingdom are leaders in the development and production of cryogenic devices, which are indispensable to creating the extremely cold conditions needed for certain quantum computers to operate. In other instances, however, the United States is reliant on China. China dominates the market for rare-earth ions, which constitute one of the most versatile materials for building QIS technologies because they can maintain their quantum states for relatively long periods of time and emit and absorb light at very specific wavelengths, making them useful for applications such as quantum communication, quantum sensing, and quantum computing. Today, China accounts for 63 percent of the world's rare-earth mining, 85 percent of rare-earth processing, and 92 percent of rare-earth magnet production.[58]

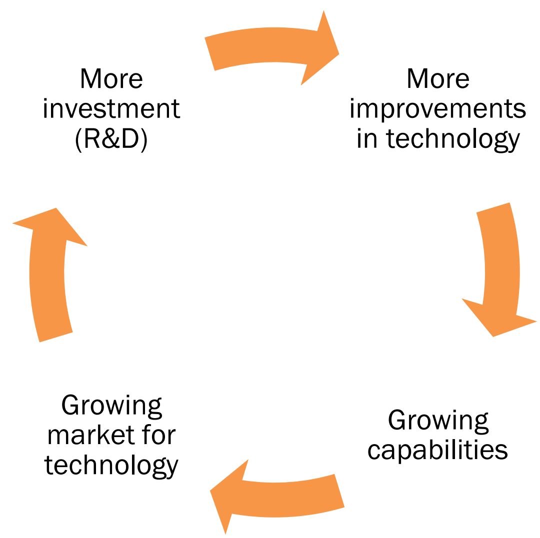
At this time, QIS technologies do not have stable supply chains because the field is constantly evolving, meaning the importance of vulnerabilities continually rises and falls. It could be the case that rare-earth ions become the de facto material for qubits in the coming years, but it could also be the case that they do not and a different implementation for quantum computers wins out. This is one reason policymakers should continually track the dynamics of the U.S. quantum supply chain and foreign government policy initiatives that may have an impact.

For near-term issues, QED-C worked with market intelligence firm Hyperion Research in 2022 to conduct a survey exploring issues QC companies may face in the next three years with supply chains for materials, components, and QC-finished products. Of the 47 respondents in U.S. industry, 58 percent of organizations said they would "experience at least some QC-related supply chain disruption that would affect their ability to either supply materials, components, or sub-assemblies to the QC sector or directly market QC-related goods and/or services."[59] When asked what would be the single most likely cause of a such a disruption, access to key raw materials and manufacturing or assembly equipment were the two most popular answers.[60]

Supporting Commercialization

The development of large-scale quantum systems, particularly quantum computers, depends on the ability to scale the smaller systems in play today. As a 2019 report from the National Academies of Sciences, Engineering, and Medicine points out, historically, growth in technological systems has resulted from a virtuous cycle wherein better technology generates more revenue, which companies reinvest in R&D, which in turn attracts both new talent and companies that have helped bring the technology to the next level (see figure 6).[61] To begin such a virtuous cycle for QIS technologies, the key will be to create a growing market for the near-term applications of quantum technologies currently under development, which in turn depends on a vibrant ecosystem of academic, government, and commercial actors.

Figure 6: Virtuous cycle for scaling a new technology



Unfortunately, U.S. policy is not sufficiently focused on supporting near-term quantum applications. Recognizing this, QED-C published a report in September 2022 pushing for the U.S. government to support public-private partnerships (PPPs) that can help accelerate near-term applications specifically for quantum computers. The report notes:

> the federal government should consider establishing a PPP or leveraging an existing PPP (e.g., QED-C) whose mission is to find possible near-term QC applications by facilitating planned interaction and cooperation among QC hardware and software experts, application domain experts, user communities, and policy and market experts. Such a partnership should be organized thematically around a significant area of public interest, such as climate and sustainability or public health, where there is an emerging critical mass of quantum R&D already underway.[62]

Several of these comments echo those the Center for Data Innovation made in its 2021 report "Why the United States Needs to Support Near-Term Quantum Computing Applications."[63] In particular, both reports call on the U.S. federal government to establish a program that challenges companies to come up with innovative quantum solutions to public sector problems. By challenging industry to develop innovative solutions for public sector needs from the demand side, the government is offering up U.S. cities as successful first customers, thereby increasing market demand for nascent near-term quantum computing technologies and enabling companies to create competitive advantage in the market.

Other countries are already pursuing this. The United Kingdom, for instance, has established a Commercializing Quantum Technologies challenge that provides around £174 million ($214 million) of government funding, supported by £390 million ($480 million) in funding from industry, for industry-led projects that address four themes of the government's industrial strategy: clean growth, aging society, the future of mobility, and artificial intelligence. As of fall 2022, this challenge had provided funding for 139 projects led by U.K.-registered businesses.[64]

The Canadian government is also focused on commercialization. In 2020, it released a request for proposals to develop "quantum computing as-a-service."[65] The goal of this challenge is for technology providers to make quantum computing accessible to domain experts in fields such as finance and logistics by creating tools that let them easily express and manipulate problems without having to understand much about how quantum computing works.[66] Such a tool is somewhat analogous to platforms such as Microsoft Azure that let businesses develop, test, and run applications through Microsoft-managed data centers, thereby insulating them from needing to know how to build and manage the platform or underlying infrastructure and allowing them to focus on the problem instead. By focusing on growing a market for quantum computing technologies, Canada is better fueling the commercial interest needed to create a snowball effect in investment. The Canadian government also released a challenge in 2022 that is "seeking pre-commercial innovative prototypes that can be tested in real life settings and address a variety of priorities within the Government of Canada."[67] This pilot project gives small and medium-sized enterprises the opportunity to sell their innovations directly to the government of Canada.[68]

Recommendations

- **Congress should direct the Department of Commerce to work with the QED-C to review the quantum supply chain and identify risks.** The United States will need comprehensive innovation and competitiveness strategies to spur investments in R&D, infrastructure, and skills in order to stay competitive, but policymakers cannot formulate effective policies and programs without first knowing what the quantum supply chain looks like today and how it is likely to develop. To mitigate supply chain vulnerabilities, the Department of Commerce should work with relevant agencies to track and assess global supply chains for critical components, materials, and equipment and submit a report reviewing the quantum supply chain to the Assistant to the President for National Security Affairs and the Assistant to the President for Economic Policy.

- **Congress should direct and fund the recently established Directorate for TIP within NSF to establish quantum testbeds for use-inspired research.** The CHIPS and Science Act charged TIP with accelerating the development of key technologies, one of which is quantum. By providing funding for a TIP-led program to establish quantum testbeds, policymakers can help ensure quantum research is effectively translated into real-world applications. Ideally, this program would encourage and support research projects that focus on near-term applications and align with regional economic development goals by fostering collaboration and partnerships between universities, local businesses, and state and local governments.

INTERNATIONAL COLLABORATION ON QUANTUM

Quantum is emerging in a geopolitical environment. The United States is rightly trying to work with like-minded partners to coordinate QIS technology development. It is also considering creating export controls to protect QIS.

Coordinated Quantum Technology Development

The United States has signed several cooperative bilateral agreements on QIS with countries including Australia, Canada, Denmark, France, Finland, India, Japan, the Netherlands, Sweden, Switzerland, and the United Kingdom. Cooperating with like-minded countries on developing QIS technologies is crucial because the expense, complexity, and scale required to innovate and manufacture necessary associated materials mean no single nation can go it alone. In the face of competition and challenges from China, allied cooperation is critical.

However, the NQIAC has found that inadequate funding is hampering U.S. efforts to act on the agreements it has made.[69] The U.S. government will need to provide new dedicated research funding to ensure that international collaborations can be scientifically productive and place the negotiation and implementation of these agreements under the leadership of an appropriate agency if it wants to see these agreements bear fruit.[70]

Europe's approach to implement international quantum collaboration is laudable and one the United States should seek to emulate. The EU has provided approximately €592,400 ($645,000) for a program called the Quantum Flagship International Cooperation on Quantum Technologies (InCoQFlag), which aims to identify win-win situations in terms of collaborations with countries investing heavily in QIS.[71] Led by the French Atomic and Alternative Energies Commission, a public research organization, the project brings together leading European research organizations in "exploring types of collaboration that would help Europe structure the best framework for the development of quantum technologies, which would benefit economic value creation and the research community as a whole."[72] The end goal is for the project to come up with a road map by the end of 2023 for international partnerships that the EU can use to set up advantageous partnerships.

Export Controls

Export controls are the rules governing the export of physical items, software, technology, and sometimes services to various destinations, uses, and users to accomplish certain national security and foreign policy (including human rights) objectives.[73] In the United States, the Department of Commerce's Bureau of Industry and Security (BIS) regulates the export of sensitive technologies, including those related to quantum technology, under the Export Administration Regulations.

BIS is in the middle of developing new export controls to thwart the progress of China's quantum computing ambitions.[74] In 2021, the agency proposed adding a new Export Control Classification Number (ECCN) in order to control quantum computers and related electronic assemblies and components, including specified qubit devices and circuits and quantum control components and measurement devices.[75] This rule also proposes controlling certain associated technology and software for the development and production of these items by updating the ECCN for "encryption commodities, software, and technology" and the ECCN for "software" for quantum.

While BIS has been considering export controls for quantum technologies for years—discussions on the topic span both the Biden and Trump administrations—concrete progress or a timeline for these efforts remains unclear. It seems the government is trying to avoid an approach that moves fast and breaks things, which makes sense given the nascent nature of the industry and the stifling impact heavy-handed export controls could have on domestic growth.

Recommendations

- **Congress should direct DOE to establish and lead a program that invites allied nations to co-invest in quantum moonshots.** While the United States has made several bilateral quantum agreements to facilitate closer collaboration with like-minded partners, the U.S. government should specifically target cooperation by enrolling allied partners in quantum moonshots with resulting intellectual property or technical discoveries shared at levels proportionate to mutual investment. DOE can model this program on the EU's InCoQFlag, which aims to identify win-win situations in terms of collaborations with countries investing heavily in QIS.

- **Congress should direct NIST to prioritize promoting U.S. participation, particularly from U.S. industry stakeholders, in international standards fora in the reauthorization of the NQIA.** As outlined in the White House's National Standards Strategy for Critical and Emerging Technologies published in 2023, it is a priority of the U.S. government to "catalyze U.S. attendance in standards development in high priority early-stage CET areas, such as quantum information technologies, where U.S. industry is nascent but standards work is ongoing."[76]

CONCLUSION

Many nations, including China, are actively pursuing advancements in quantum. Several countries and regions such as the United Kingdom, Australia, and EU have launched extensive research initiatives and programs aimed at bolstering their positions in quantum—and some of these outstrip the United States in scale and scope, making the United States' leadership in quantum far from assured.

Quantum technologies are not only important for national security, but they also have the potential to exert a transformative influence on the economy and society. Being at the forefront of this technological frontier is strategically crucial for the United States in terms of both its economic and societal well-being. The U.S. government should take proactive measures immediately to maintain its leadership position.

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ABOUT THE CENTER FOR DATA INNOVATION

The Center for Data Innovation studies the intersection of data, technology, and public policy. With staff in Washington, London, and Brussels, the Center formulates and promotes pragmatic public policies designed to maximize the benefits of data-driven innovation in the public and private sectors. It educates policymakers and the public about the opportunities and challenges associated with data, as well as technology trends such as open data, artificial intelligence, and the Internet of Things. The Center is part of the Information Technology and Innovation Foundation (ITIF), a nonprofit, nonpartisan think tank.

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