A Report of the

National Quantum Initiative Advisory Committee

June 2023

Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science

ABOUT THE NATIONAL QUANTUM INITIATIVE ADVISORY COMMITTEE

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal Advisory Committee called for in the National Quantum Initiative (NQI) Act to advise the President, the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), and the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX), and to make recommendations for the President to consider when reviewing and revising the NQI program. It is tasked with conducting independent and periodic assessments of trends and developments in quantum information science and technology (QIST); the management, coordination, implementation, and activities of the NQI; whether goals established in the NQI Act are helping to maintain U.S. leadership in QIST; whether a need exists to revise the NQI; whether opportunities exist for international cooperation with strategic allies; and whether national security, societal, economic, legal, and workforce concerns are adequately addressed by the NQI. The NQIAC is also tasked with submitting reports with its independent assessments to the President and appropriate committees of Congress, including any recommendations for improvements to the NQI. The NQIAC consists of leaders in the field from industry, academia, and Federal laboratories. More information is available at https://www.quantum.gov/about/nqiac/.

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ABOUT THE NATIONAL QUANTUM COORDINATION OFFICE

The National Quantum Coordination Office (NQCO) coordinates quantum information science (QIS) activities across the U.S. Federal Government, industry, and academia. Legislated by the NQI Act of 2018 and established within the White House Office of Science and Technology Policy, the NQCO oversees interagency coordination of the NQI program and QIS activities; serves as the point of contact on Federal civilian QIS activities; ensures coordination among consortia and various quantum centers; conducts public outreach, including the dissemination of findings and recommendations of the SCQIS, ESIX, and NQIAC; and promotes access to and early application of the technologies, innovations, and expertise derived from U.S. QIS activities, as well as access to quantum systems developed by industry, universities, and Federal laboratories to the general user community. More information is available at https://quantum.gov.

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EXECUTIVE SUMMARY

Decades of technological progress in quantum information science and technology (QIST), stemming from sustained U.S. funding of fundamental and applied research and development, has enabled the exploration and manipulation of quantum phenomena in ways never before possible. QIST seeks to understand and harness these quantum phenomena to develop revolutionary technologies in quantum computing and simulation, networking and communication, and sensing and metrology. Ongoing efforts across the U.S. Government, national laboratories, universities, and corporations are working to realize the full potential of QIST, requiring a multidisciplinary approach that includes quantum mechanics, materials science, computer science, engineering, and mathematics.

To coordinate these efforts, ensure continued leadership, and accelerate U.S. progress in QIST, Congress established the National Quantum Initiative (NQI) program in 2018. The NQI was legislated to be a ten-year program; however, its science activities were only authorized for five years, through September 30, 2023. Given the success of the program thus far and the potential of QIST R&D to yield transformative technologies, the NQIAC strongly recommends that the NQI be continued and strengthened according to the following overarching recommendations:

A. To ensure U.S. leadership in QIST, the NQI Act should be reauthorized and expanded. All authorized QIST programs in the NQI Act, the CHIPS and Science Act, and other relevant legislation should be funded at the authorized levels.
B. To ensure that the United States leads in QIST discovery, innovation, and impact, efforts should be increased to attract, educate, and develop U.S. scientists and engineers in QIST-related fields, improve and accelerate pathways for foreign QIST talent to live and work in the United States, and increase support for research collaboration with partner nations.
C. To safeguard the security and competitiveness of U.S. advances in QIST, the United States should develop policies that thoughtfully promote and protect U.S. leadership in QIST; expand domestic center-scale and single principal investigator QIST research activities and infrastructure; and evaluate and improve the reliability of global supply chains for QIST.
D. To realize the potential of QIST for society, the NQI must accelerate the development of valuable technologies. This goal will require new programs in engineering research and systems integration that will enable a virtuous cycle of maturing and scaling of quantum systems to useful applications through multisector partnerships and engagement with end-users.

This report provides detailed recommendations for the U.S. Government to renew the NQI Act, enhance U.S. QIST research activities, fund partnerships with industry, invest in infrastructure for QIST, promote international cooperation, support and protect U.S. QIST R&D, strengthen supply chains, retain foreign talent, and develop domestic talent in QIST. A whole-of-nation approach that leverages the strengths of all sectors will be necessary to address fundamental science and engineering challenges and realize the benefits of QIST.

INTRODUCTION

The Potential of Quantum Information Science

Quantum information science (QIS) seeks to use the laws of quantum physics for the storage, transmission, processing, and measurement of information. The United States has long supported research and development (R&D) in quantum physics, leading to critical technologies such as lasers, the Global Positioning System (GPS), and magnetic resonance imaging (MRI). Since the emergence of QIS in the 1980s and 90s, major strides have been made to advance the theory and experimental capabilities needed to control and leverage quantum superposition and entanglement for encoding and processing information. The field of QIS is rapidly evolving and holds the potential to yield transformative technologies for sensing, computing, and networking. In recent years, governments around the world have recognized the potential of QIS to yield next-generation technologies and launched targeted investments to drive scientific advancement and progress in QIS.

The United States National Quantum Initiative

The National Quantum Initiative (NQI) Act of 2018 established a national program in QIS to accelerate American leadership and advance its related technology applications. The NQI Act and subsequent legislation (described in Box 1) continued to build a whole-of-government effort in QIS that leverages ongoing programs and catalyzes new agency programs and collaborations across all sectors. For example, the NQI Act enabled the launch of five Department of Energy (DOE) National QIS Research Centers and five National Science Foundation (NSF) Quantum Leap Challenge Institutes (hereafter referred to as NQI Centers) and the Quantum Economic Development Consortium (QED-C), an industry consortium established with support from the National Institute of Standards and Technology (NIST).

Three Federal coordinating bodies, codified in statute, facilitate interagency planning and collaboration and act as stewards of the NQI: the National Quantum Coordination Office (NQCO), the National Science and Technology Council (NSTC) Subcommittee on QIS (SCQIS), and the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX). The guiding principles for implementation and coordination of the NQI are described in the *National Strategic Overview for Quantum Information Science*,[1] which sets the Nation's strategy for ensuring continued leadership in QIS around six pillars: science, workforce, industry, infrastructure, security, and international cooperation. Under the auspices of these Subcommittees, the National Strategic Overview has been augmented by additional reports and strategy documents, including those on quantum frontiers, quantum networking, quantum sensing, and workforce development, all of which can be found on quantum.gov.[2]

As of 2023, the NQI program encompasses contributions from across the Federal Government and includes the more than 20 agencies with membership in the SCQIS and ESIX.[3] As a result of this initiative, Federal spending for QIS research and development (R&D) roughly doubled between FY 2019 and FY 2022 to more than $900 million dollars per year.[4]

[1] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[2] https://www.quantum.gov/publications-and-resources/publication-library/
[3] https://www.federalregister.gov/executive-order/14073
[4] https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf

Box 1. Highlights of Authorizations in Key QIS Legislation

National Quantum Initiative Act of 2018 (Public Law 115-368)

- Authorized NIST to
  - Expand support of basic and applied QIS and technology R&D, and
  - Establish a quantum industry consortium.
- Authorized NSF and DOE to establish up to five new QIS Research Centers each.
- Codified Federal coordinating and advisory bodies: NQCO, SCQIS, NQIAC.

National Defense Authorization Acts (NDAAs) for FY 2019, 2020, and FY 2022 (Public Law 117-81)

- Authorized the Department of Defense (DoD) to carry out R&D on QIS and QIS technologies, coordinated with the NQCO and SCQIS, and designate QIS Research Centers within the DoD services.
- Amended the NQI Act to codify ESIX, as well as provide additional responsibilities to ESIX.

CHIPS and Science Act of 2022 (Public Law 117-167)

- Amended the NQI Act to codify NIST's role in
  - Conducting research for the standardization of quantum and post-quantum classical cryptography;
  - Developing quantum networking and sensing technologies and applications; and
  - Providing support to other Federal agencies developing infrastructure for QIS technologies that have reached sufficient levels of readiness.
- Amended the NQI Act to require the SCQIS to update the national strategy for quantum networking by 2026.
- Codified NSF's new Technology, Innovation, and Partnerships (TIP) directorate and establishes quantum information science and technology as an initial key technology focus area.
- Authorized the NSF Quantum Education Pilot Program to incorporate QIS into science, technology, engineering, and mathematics (STEM) curricula at all education levels.
- Authorized the DOE Quantum Network Infrastructure Program and the Quantum User Expansion for Science and Technology (QUEST) Program.

Purpose of this Report

The National Quantum Initiative Advisory Committee (NQIAC) was authorized under the NQI Act and elevated to a Presidential advisory committee in May 2022 by Executive Order 14073.[5] The NQIAC met in December 2022 to launch its first assessment of the NQI, with the purpose of making recommendations to enhance the initiative. The NQIAC co-chairs established three subcommittees and tasked each with addressing two of the six pillars from the National Strategic Overview for QIS. The subcommittees met approximately weekly from January 18 through May 12, 2023, gathering information through interviews with experts from Federal agencies, NQI and NDAA QIS Research Centers, universities, industry, and other organizations. Upon reviewing these inputs, academic literature, and policy documents, the subcommittees shared draft findings and recommendations with the full NQIAC at a public meeting on March 24, 2023. The subcommittees subsequently refined their findings and recommendations, which

[5] https://www.federalregister.gov/documents/2022/05/09/2022-10076/enhancing-the-national-quantum-initiative-advisory-committee

were discussed in plenary by the committee as a whole and passed by consensus vote at another public meeting on May 19, 2023.

This report constitutes the NQIAC's consensus findings and recommendations for the United States to sustain U.S. leadership in QIS.

NQIAC FINDINGS ON THE CURRENT STATE OF THE NQI

1. **In its first five years, the NQI has increased the United States' capacity in quantum information science and technology R&D.**

   The NQI Centers have stimulated new, cross-disciplinary, and multi-institutional collaborations across all sectors—collaborations that would not otherwise have occurred. Important new scientific discoveries have already emerged from these efforts, including demonstrated advances in the technologies required to scale quantum systems. NQI Centers have successfully leveraged long-standing Federal investments in R&D infrastructure, such as nanomaterials fabrication centers and DOE beamlines.

   The NQI has also improved coordination of quantum information science and technology (QIST) R&D activities across sectors and across U.S. Government agencies and helped to enhance awareness of QIST R&D and its likely benefits to society. In addition to Federal QIST funding, the NQIAC finds that private sector and university investments in QIST R&D have also increased since the establishment of the NQI. As is generally true for U.S. R&D investments, funding for QIST R&D helps build a QIST workforce, because the funded research creates opportunities for student and teacher engagement and training.

   Since the establishment of the NQI, other nations and regions have announced national strategies for QIST R&D, along with increased and substantial funding commitments that are projected to rival that of the United States.[6] Continued and increased funding for the next five years of the NQI and beyond will be necessary for our Nation to lead the global competition in QIST.

2. **The development of QIST is critical to U.S. economic and national security.**

   A strong economy is an essential component of national security and can be sustained and grown through continued competitiveness in emerging technology areas. Next-generation QIS technologies will exist on a spectrum spanning quantum sensing, quantum computing, and quantum networking, with some applications already known and others expected to emerge in the wake of new discoveries. Advanced quantum sensors will likely be the first quantum information technologies to be commercialized, providing potential near- and medium-term improvements to precision navigation and timekeeping, environment and climate sensing, and biomedical sensing. In the longer term, quantum computers realized at scale could solve commercial and mission-focused problems that are intractable on classical computers—for

[6] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf; https://qureca.com/quantum-initiatives-worldwide-update-2023/; https://iopscience.iop.org/article/10.1088/2058-9565/ab4bea/pdf; https://iopscience.iop.org/article/10.1088/2058-9565/ab4346/pdf

example, certain problems in quantum chemistry or materials science whose answers could inform the design of new medicines or materials. Quantum networks could enable distributed quantum sensors for improved measurements, as well as larger-scale or distributed quantum computation across many quantum processors.

3. Key scientific, engineering, and systems integration challenges remain and must be solved for the United States to realize the full economic impacts and benefits of QIST.

During the first five years of the NQI, substantial scientific progress has been made in QIST, including at large, interdisciplinary QIS Research Centers leveraging partnerships across academia, industry, and Federal and national laboratories. Due to the field's nascence, the transition from R&D to commercialization and deployment has so far been limited. Quantum sensing, which currently has the highest technology readiness level when compared to other quantum technologies, is poised to make the most immediate impact. Until technologies mature, market demand will remain insufficient to establish a robust supply chain for QIST R&D, relegating important components and materials to only a few and sometimes unreliable sources. While industry activities are advancing rapidly, industry participation in NQI Centers has been somewhat limited to date, in part due to administrative and intellectual property (IP) requirements that slow or inhibit collaboration.

Historically, industry has been essential in translating emerging technologies from lab to market. The lab-to-market translation of QIST from foundational science to commercial products and services faces long timelines and large development costs. The NQIAC believes that without more industry engagement in the NQI, driven by commercial and agencies' mission needs, the United States could be placed at a disadvantage relative to our near-peer competitors. By ensuring there is a strong and healthy industry, the United States will be well positioned to continue leading the technological and engineering progress in QIS.

NQIAC RECOMMENDATIONS

As we look toward the future, the NQI should continue to be grounded in scientific discovery with an increase in efforts to realize the economic and societal benefits of QIST. This new phase will necessitate a ramp up of investments in fundamental research across engineering, systems integration, software, and applications discovery in order to mature and scale quantum systems into relevant technologies. The NQIAC's four overarching recommendations for U.S. leadership in QIST over the next five years and beyond are highlighted in Box 2.

The NQIAC has developed nine detailed recommendations for achieving these objectives, described in the following sections. To summarize, they are:

1. Reauthorize and appropriate the NQI Act
2. Expand research
3. Fund industry-led partnerships
4. Invest in equipment and infrastructure
5. Promote international cooperation
6. Promote and protect U.S. QIST R&D
7. Strengthen supply chains
8. Develop domestic talent
9. Attract and retain foreign talent

Some of these recommendations detailed below focus on the need to reauthorize and expand the NQI Act; several apply more broadly to the NQI program.

Box 2. Overarching Recommendations for U.S. QIS Leadership

A. To ensure U.S. leadership in QIST, the NQI Act should be reauthorized and expanded. All authorized QIST programs in the NQI Act, the CHIPS and Science Act, and other relevant legislation should be funded at the authorized levels.
B. To ensure that the United States leads in QIST discovery, innovation, and impact, efforts should be increased to attract, educate, and develop U.S. scientists and engineers in QIST-related fields, improve and accelerate pathways for foreign QIST talent to live and work in the United States, and increase support for research collaboration with partner nations.
C. To safeguard the security and competitiveness of U.S. advances in QIST, the United States should develop policies that thoughtfully promote and protect U.S. leadership in QIST; expand domestic center-scale and single principal investigator QIST research activities and infrastructure; and evaluate and improve the reliability of global supply chains for QIST.
D. To realize the potential of QIST for society, the NQI must accelerate the development of valuable technologies. This goal will require new programs in engineering research and systems integration that will enable a virtuous cycle of maturing and scaling of quantum systems to useful applications through multisector partnerships and engagement with end-users.

RECOMMENDATION 1: The United States should renew the NQI to support U.S. quantum information science, technology, and engineering, and signal intent to extend the NQI beyond its initial ten-year authorization.

The NQIAC finds that the NQI Centers are gaining momentum in scientific discoveries, contributions, and advances across QIS. To move toward realizing technologies with economic and security benefits for the Nation, the United States must continue to build on and explore fundamental science and invent and develop innovative technologies for engineering quantum systems. Doing so will position the United States to lead and capitalize on future applications of quantum sensing, quantum computing, and quantum networking.

The NQIAC recommends that funding be increased in gap and growth areas as suggested in the following sub-recommendations, in addition to maintaining the NQI's science-first goals. The United States should also signal the intent to extend the NQI beyond 2028 (the original ten-year window), providing the certainty necessary to help researchers and Centers plan and achieve more impactful research over the longer term and attract top talent.

- **Recommendation 1A: Authorization for NQI centers should be renewed for at least five years, with existing Centers charged to review and refresh their R&D goals, and all authorized funds should be appropriated.**

  While the NQI was established as a ten-year effort, the NQI Centers were initially authorized for only five years.[7] The NQIAC believes that support beyond the ten-year sunset in 2028 is needed to realize the scientific and fundamental engineering breakthroughs that will lead to new

[7] https://www.congress.gov/bill/115th-congress/house-bill/6227

applications of QIST. By assuring sustained support for the NQI programs, researchers will be better positioned to address crucial long-term challenges, such as scaling and integrating quantum systems for end-use applications. For comparison, the United Kingdom has expressed a longer-term commitment than the United States; it recently announced a ten-year £2.5 billion ($3B) quantum research and innovation program to run from 2024-2034, which builds on over £1 billion ($1.2B) of investment from 2014-2024.[8]

QIST continues to advance rapidly, and new discoveries and capabilities continue to shift the landscape of what is possible. NQI Center researchers may wish to shift focus or pursue new research questions as they arise; reauthorization of the NQI Centers should support the flexibility necessary to meet such opportunities. Another round of NQI funding should be authorized and appropriated for NQI Centers for an additional five years at levels necessary to capitalize on their current momentum. The NQIAC notes that funding for both NSF and NIST did not meet amounts authorized in the first five years of the NQI.

- **Recommendation 1B: CHIPS and Science Act-authorized funding for QIST should be appropriated, and semiconductor research and manufacturing capabilities should be leveraged for QIST.**

  As summarized in Box 1, the CHIPS and Science Act authorized several QIST-relevant activities. It codified the new NSF Technology, Innovation, and Partnerships (TIP) directorate, which specializes in translating technologies from lab to market, and established QIST as an initial key technology focus area. The NQIAC recommends that NSF receive appropriations for TIP to make investments to accelerate key quantum technologies, consistent with Recommendation 3 and Recommendation 7C. The CHIPS and Science Act also authorized the NSF Education Quantum Pilot Program for incorporating QIS into STEM curricula at all education levels, a DOE program on quantum networking infrastructure, and the DOE Quantum User Expansion for Science and Technology (QUEST) program to provide researchers with access to quantum computing hardware to aid in research on algorithms and software and the development of applications. These programs have not been appropriated, however, and the NQIAC recommends that they be funded. The importance of the NSF QIS STEM program is further described in Recommendation 9B, and the significance of the QUEST program is expounded upon in Recommendation 2D.

  The CHIPS and Science Act makes significant investments to increase semiconductor fabrication capabilities in the United States. The NQIAC recommends these investments address the unique needs of emerging technologies like QIST, develop programs to onshore QIST-related component technologies, and expand access to infrastructure for QIST. In turn, the unique requirements of QIST R&D will push the frontier of semiconductor manufacturing, forming a virtuous cycle of scientific development and lab-to-market translations of technologies.

[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1142942/national_quantum_strategy.pdf

RECOMMENDATION 2: The United States should expand the NQI to increase support for fundamental research in quantum information science and engineering.

- **Recommendation 2A: Federal agencies should be authorized to establish additional nimble and focused NQI Centers, as needed, to address newly emerging scientific questions.**

  QIST is a broad, rapidly growing field of research. New, yet-to-be-made discoveries are likely to present opportunities for progress in unanticipated research frontiers, such as through efforts to integrate and scale quantum systems as described in Recommendation 3. The original NQI Act language precludes creating new Centers to address these new research areas. NSF and DOE should be granted the authority to establish or designate new Centers in addition to the five each agency has established under the NQI, so that the United States can pursue new leading-edge research areas as they emerge. The NQIAC believes that such new Centers should be established at a scale that enables nimble, focused research collaborations on emerging opportunities, analogous to what has occurred at the NSF Quantum Leap Challenge Institutes. The opportunity for researchers to compete for new center-scale awards will also stimulate new thinking and cross-disciplinary collaborations, as well as harness enthusiasm as the NQI continues.

- **Recommendation 2B: In addition to the NQI Centers, agency programs to fund QIS research activities led by a single principal investigator or only a few principal investigators should be authorized and appropriated.**

  While NQI Centers provide an important framework for interdisciplinary and cross-sector collaboration, fundamental and disruptive advances in QIST often come from individual laboratories or smaller-scale collaborations. For future research progress, funding for center-scale collaborative activities should be balanced with concomitant funding for research activities led by a single principal investigator or only a few principal investigators. Agencies should also increase the size of grants to individual contributors, as the purchasing power of present awards sometimes no longer covers the full cost of QIST research.

- **Recommendation 2C: The NQI should increase support for fundamental research in engineering to accelerate the development of quantum technologies for future scientific and commercial applications, including by establishing QIST Centers that focus on engineering of integrated and scaled systems for a variety of quantum platforms and technologies.**

  Given that many QIS technologies are still in early research stages, the NQI's science-first approach has been important for advancing these fields. The NQIAC finds that an emphasis on science remains important to the United States' long-term competitiveness in QIST. At the same time, new scientific progress increasingly requires new approaches and methods for developing controls or engineering of quantum systems, enabling a virtuous cycle of development.

  The NQIAC finds that a concerted effort is needed to develop the fundamental abstractions—the "engineering rules" that enable the practical application of fundamental physical concepts in larger systems—necessary to instantiate quantum engineering as a discipline. As the discipline develops, and through attempts to build increasingly larger quantum systems, iterative feedback between QIS and engineering advances will help solve problems critical to the future integration and implementation of commercial quantum systems. For example, in the area of quantum computing, fundamental engineering developments can give rise to innovative enabling

technologies that will allow more efficient integration of quantum circuits and software stacks in industrial testbeds, which allows closer feedback between industry and academic research efforts. Agencies administering these Centers should take steps to minimize hindrances to industry participation, including streamlining and reducing burdensome IP requirements or constraints.

- **Recommendation 2D: Federal agencies should increase investment in R&D for quantum computer science and software engineering, including in quantum algorithms, applications, software and software development tools, and error correction.**

  As quantum computing platforms scale in capabilities and complexity, it is increasingly important to invest in quantum computer science research, especially to develop new techniques for mitigating and removing errors in quantum systems and identifying applications that will provide commercial value. Collaboration with potential end-users will be vital to identifying promising application areas as progress is made toward practical quantum solutions.

  These advances should be informed by development and testing on hardware. The QUEST program, authorized in the CHIPS and Science Act (see Recommendation 1B), would support some of this work by providing U.S. researchers with access to cloud-based commercial quantum computing platforms for R&D. In addition, funding for access to commercial systems helps drive investment by industry in system innovation and development, driving a virtuous cycle of science and engineering development with industry, just as observed when commercial high-performance computing (HPC) systems were supported for software research.

  Concurrent to these investments, NSF should fund basic research on the cybersecurity of QIS technologies to ensure that IP is protected and QIS technologies are not used for illicit purposes.[9] This could include protecting software that is executed on cloud-based quantum computing platforms, protecting hardware that is accessible on the cloud, and ensuring that cloud-based quantum computers are not used for nefarious purposes.

RECOMMENDATION 3: New Federal programs should help fund industry-led partnerships to develop and advance scaled-up, integrated quantum systems for mission- and commercial-grade technologies, and new mechanisms to fund such programs should be defined and authorized as needed.

The NQIAC believes that for the United States to lead in the development of QIST, the U.S. Government must act to accelerate progress toward economically-valuable and commercially-viable QIST systems and use cases. To do so, the NQIAC believes the U.S. Government should fund industry-driven QIST projects that enable the integration of test platforms focused on system-level demonstrations in real-world operating environments, in collaboration with potential end-users, which will help early-stage technologies move towards commercialization.

With each effort to build larger or more complex systems, new fundamental science and engineering questions emerge and can be addressed in an iterative and collaborative process between industry,

[9] https://www.quantum.gov/wp-content/uploads/2022/11/2022-Workshop-Cybersecurity-Quantum-Computing.pdf

academia, Federal and national laboratories, and agencies. For example, existing noisy intermediate-scale quantum (NISQ) computers are being developed through significant industrial investment, but the necessary engineering investments to create higher efficiency cryogenic systems, lower-power control and measurement hardware (including optical and radio frequency components and cryogenic semiconductors), and the system engineering to tie low-level quantum device controls to higher levels of the hardware and software stack are all areas of engineering research that need to begin now. By working alongside industry, Federally-funded academic and government researchers will significantly accelerate, and increase the likelihood of success of developing scaled QIST integration. This effort needs to focus on integrating systems beyond a five-to-ten-year horizon, going beyond thousands of qubits for quantum computing or developing more advanced quantum networking and sensing platforms.

RECOMMENDATION 4: Agencies should expand investment in small- and mid-scale infrastructure in support of Federally-funded research that includes support for staff, equipment, maintenance, and operating costs, to ensure that facilities meet the needs of QIST projects.

While large-scale, shared-use infrastructure investments have been established or leveraged by the existing Centers, the NQIAC finds that it can be challenging for researchers to request and obtain access to this infrastructure on the timescales needed to achieve rapid, iterative progress. Fundamental research often requires more flexibility than can be accommodated by a large-scale facility. For example, researchers may need different types of tools, benefit from non-standard experimentation with established tools to develop new and unconventional techniques, or require several unexpected steps of iteration to perfect a process or method in pursuit of a new and exciting, but possibly challenging, capability. The NQIAC found that existing university facilities employed by QIST researchers were often designed to address technology needs that differ from the needs of QIST. The NQIAC found that some Nanoscale Science Research Centers may not have or even allow some materials in their facilities that are required for sectors of QIST research. Updating and expanding the Nanoscale Research Centers, consistent with the Nanoscale Science Research Center Recapitalization project authorized under the CHIPS and Science Act, would better serve the QIST R&D community and provide ancillary benefits to the nanoscience and semiconductor field as well.

Researchers would also benefit from funds to support small-scale ($1 to $5 million) and mid-scale ($5 to $25 million) infrastructure to nurture new research ideas. Small-scale infrastructure includes institutional laboratory equipment and facilities; mid-scale infrastructure includes multi-institution instrumentation or regionally-accessible facilities. Such investments would also assist researchers in determining which toolsets should ultimately be used in large-scale facilities in order to build next-generation quantum platforms. Such investments should accelerate the pace at which the QIST community will learn about the most promising platforms for quantum technologies.

Such funds should also support investment in the built environment into which research equipment is placed. Building infrastructure—including heating, ventilation, and air-conditioning systems, water lines, and the buildings themselves—at universities and industrial facilities requires upkeep to accommodate the specifications of QIST laboratory equipment. Universities with small endowments and small companies especially risk falling behind.

RECOMMENDATION 5: The U.S. Government should provide new dedicated funding to ensure that international cooperation statements result in productive collaborative activities between participating nations.

QIST is a global enterprise; many countries are funding research in QIST, including through national or international initiatives. U.S. progress in QIST will be accelerated through collaboration with foreign partners. In recognition of the importance of international collaboration, the United States has signed statements to facilitate collaboration with partners in QIST R&D with Australia, Denmark, Finland, France, Japan, the Netherlands, the Republic of Korea, Sweden, Switzerland, and the United Kingdom. For these statements to yield results, these international collaborative research initiatives need to be funded and coordinated by the appropriate U.S. agencies.

RECOMMENDATION 6: The Nation must simultaneously accelerate progress in QIST and protect quantum technologies from malign actors.

QIS technologies now under development may prove to be dual use and could pose threats to U.S. national security. For example, quantum computers could compromise currently deployed cryptosystems, threatening sensitive communications that rely on such protections. These same quantum computers could also help solve some of the most challenging problems facing our planet and humanity. The theft of U.S. QIS and related technologies could provide competitors with an advantage in industries based on QIST. Accordingly, the U.S. Government has to consider security issues in the design and implementation of its QIST research programs. It should proactively educate and assist domestic companies and institutions in improving their cybersecurity and R&D security procedures.

Measures to protect U.S. intellectual capital in QIST could be counterproductive if they impede developments in the basic science and technology needed to sustain U.S. progress, or if they disadvantage U.S. corporations relative to foreign competitors. The free exchange of ideas accelerates U.S. researchers' advances and U.S. leadership in QIST. Measures that restrict collaboration between U.S. and foreign researchers, or that discourage foreign graduate students from engaging in QIST research at U.S. universities or companies, could slow progress and dissuade talented QIST scientists and engineers from working in the United States.

- **Recommendation 6A: Governmental entities should implement only protective measures that are clear, appropriately targeted, and compatible with the goal of facilitating progress in QIST for the benefit of the Nation and the world.**

  To balance support for rapid progress in QIST with protections for quantum technologies developed in the United States, government entities responsible for controlling regulations or exports of QIST or classifying quantum technologies should explicitly weigh the benefits of these measures against the potential costs of slowing scientific and technological progress. As part of this effort, interagency committees that make recommendations regarding quantum technology protections should ensure they communicate with those in the QIST community who can best help them assess such tradeoffs. Entities should consider a deemed export carveout, for example, employing end user-based or use-based export controls, as opposed to list-based export controls.

- **Recommendation 6B: U.S. Government entities should frequently reassess the efficacy of protective measures as QIST advances. This review process should entail thorough consideration of the balance between managing risk and impeding progress.**

  Because of the speed with which QIST is advancing, existing controls on QIST may become unnecessary if widely available technologies have leapfrogged the original technology that was protected. At the same time, exploratory research sometimes yields advances that may pose national security risks. By frequently reassessing protective measures, U.S. Government entities responsible for controlling sensitive technologies would remove unnecessary impediments to research while responding promptly to newly recognized threats.

- **Recommendation 6C: The U.S. Government should work with partner nations to establish shared measures for ensuring supply chain resilience and for protecting QIST. It should avoid unilateral controls when they impede the ability of U.S. industry to compete in the global marketplace.**

  To ensure that U.S. measures are effective in preventing adversaries from acquiring sensitive quantum technologies, the U.S. Government should coordinate its efforts with foreign partners so that the same or similar measures may be implemented by all cooperating countries. Protection measures that are shared by all QIST-capable partner countries are more effective at preventing foreign adversaries from acquiring sensitive technologies and are more likely to prevent harm to U.S. economic and national security.

- **Recommendation 6D: Once the new post-quantum cryptography (PQC) standards are published, the United States should proceed expeditiously with migration to PQC in the public and private sectors. The U.S. Government should provide appropriate resources to accomplish this task effectively, thoroughly, and efficiently.**

  National Security Memorandum 10 (NSM-10) on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems, signed by the President in 2022, emphasizes the urgency of protecting vulnerable U.S. cryptographic systems from threats posed by future quantum computers. NSM-10 directs NIST, in coordination with other agencies, to guide the migration to PQC in the private sector, and directs the National Security Agency (NSA), in coordination with other agencies, to manage migration to PQC for national security systems. The current target date for migration of Federal systems is 2035; an earlier completion date would be highly preferable and should be achievable through vigorous U.S. Government action.

  The U.S. Government is concerned that some sectors of the U.S. economy, especially small businesses, will not be able to adopt the new encryption standards rapidly. To ensure that personal and business data are protected in a post-quantum world, the U.S. Government should provide appropriate incentives and resources to encourage people and businesses to make the transition promptly. If the migration is not expeditious, U.S. citizens will remain vulnerable to the future loss of important proprietary and personal data.

RECOMMENDATION 7: The U.S. Government should facilitate efforts to strengthen, diversify and secure QIST supply chains domestically and in collaboration with partner nations. As QIST progresses, measures to de-risk and secure international supply chains should be continually updated.

The QIST industry is developing quickly, but market demand for QIST is still insufficient to support a robust supply chain. For many key pieces of equipment or components, only one or two companies manufacture the products worldwide. In addition, some components are manufactured from materials that are only available from a few sources. As the QIST industry expands, critical supplies of components, equipment, or materials may be under the control of adversarial countries, which could exploit these vulnerabilities to disrupt the QIST industry in the United States and partner nations.

- **Recommendation 7A: The Department of Commerce, in coordination with industry, should develop and maintain a QIST supply chain risk analysis and a plan for strengthening, diversifying, and securing supply chains for key QIS technologies.**

  To mitigate supply chain vulnerabilities, the United States and its partners should track and assess global supply chains for critical components, materials, and equipment so that policymakers can assess supply chain risks and take steps to reduce those risks, if needed. These risk analyses should, for example, enumerate the layers of a quantum technology stack, identify important technologies for which there are limited U.S. and partner nation suppliers, and characterize the risk to those technologies from political instability and purposeful disruption. These supply chain analyses should be regularly reviewed and updated as QIST progresses to ensure that the United States and partner governments remain informed about supply chain vulnerabilities.

  Based on the results of the supply chain risks analyses, the U.S. Government should develop a plan to strengthen, diversify, and secure QIST supply chains. This plan should address how the Department of Commerce (DOC), DOE, and other relevant agencies will develop supply chain capacity for shared critical elements, minerals, isotopes, components, or infrastructure needed by the U.S. QIST industry.

  Elements of the plan should address how the U.S. Government can:

  - Support small businesses, e.g., by leveraging the existing Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs with QIST-focused initiatives, using Direct to Phase II contracts funded at the statutory maximum, or by raising the cap on SBIR awards to allow for further development and commercialization of promising hardware.
  - Promote R&D investment at startup, small, and emerging technology companies by expanding R&D tax credit legislation.
  - Build complementary and diverse manufacturing and research capabilities across allied nations.
  - Enable the verifiability of provenance, quality, or security of raw materials or components through international engagements, support the development of standards that enhance security, facilitate international trade, and strengthen trade enforcement mechanisms to counter unfair practices.
  - Coordinate with partner nations on these and other supply chain-related activities.

- **Recommendation 7B: The U.S. Government should follow and potentially expand the DOE roadmap for addressing critical isotope and rare element needs for QIS R&D to ensure future supplies, as some isotope production requires substantial lead time.**

  Some critical isotopes or rare elements necessary for QIST R&D are presently sourced or manufactured outside of the United States, including some by foreign adversaries, which risks inhibiting access by U.S. researchers. One example is holmium, which is used in cryogenic coolers necessary to cool certain kinds of quantum information processing hardware. While other critical isotopes, such as ^{3}He and ^{28}Si, are provided by the U.S. Government, any efforts to boost supply or production in response to research needs require long lead times to establish.

  DOE should implement a comprehensive plan for robust sourcing of isotopes and rare elements. This plan should project future demand for isotopes and rare elements to allow time to ramp up indigenous production or secure viable sources from partner nations. DOE and DOC should collaborate to implement this plan. Such a plan should seek to enable verification of the quality of supply; collaboration and cooperation of global supply, especially with nations engaged in a QIST partnership; and the ability to prove provenance of supply.

- **Recommendation 7C: Federal agencies should actively support the development of QIST-enabling technologies to help de-risk the domestic QIST supply chain.**

  From dilution refrigerators to lasers, enabling technologies play a key role in the QIST supply chain. As a part of efforts to bolster the domestic and allied-nation QIST supply chain, Federal agencies, such as DOC or DoD, should ensure a competitive and healthy marketplace by actively supporting enabling technologies for QIST. Potential avenues could include funding the development and customization of component technologies, and the bulk procurement of key technologies by the U.S. Government to be used by U.S. researchers.

RECOMMENDATION 8: Domestic talent in QIST should be expanded through educational and training programs at all levels.

Given the expected growth of the QIST industry in the United States, the NQIAC believes the current pathways through which workers enter the QIST industry will not meet domestic QIST industry demand. The NQIAC believes that the U.S. Government needs to implement several measures to ensure the U.S. QIST industry has the ability to attract, hire, and retain sufficient numbers of well-trained workers to meet current and future workforce needs. Expansion of pathways to employment in QIST at all stages will be required to maintain U.S. competitiveness and leadership in QIST in the coming decades.

In February 2022, the SCQIS delivered its QIST Workforce Development National Strategic Plan, which included an assessment of the current QIST workforce landscape, in addition to recommended actions for government, academia, industry, and the QIST ecosystem around topics such as outreach and education, professional training, and accessibility and equity in QIST careers. The NQIAC endorses the recommendations from the QIST Workforce Development National Strategic Plan, and recommends the following specific actions, many of which align with it. Moreover, it is the opinion of the NQIAC that to meet current and near-term workforce demand, the specific recommendations articulated below should all be implemented immediately.

- **Recommendation 8A: Federal agencies should create additional fellowships and traineeships for U.S. citizens and permanent residents pursuing QIST-related degrees with a focus on broadening participation.**

  The U.S. Government should increase opportunities for all Americans to join the QIST workforce. To increase the supply of QIST workers who are U.S. citizens or permanent residents, new fellowships and traineeships are needed to provide funding and hands-on experience in QIST. Efforts should be made to recruit historically underrepresented demographic groups into these programs to increase the pipeline of talent into QIST.

  - NSF could create a quantum version of the Computer and Information Science and Engineering (CISE) Graduate Fellowships (CSGrad4US), which could provide mentoring to students from underrepresented demographic groups to help them enroll in QIST-related PhD programs.
  - NSF could create a QuantumCorps scholarship-for-service program, similar to the ongoing NSF-run CyberCorps program—also recommended in the QIST Workforce Development National Strategic Plan—to help address shortages of QIST researchers in the Federal workforce.[10]
  - NSF and other Federal agencies should continue to leverage existing graduate fellowships, such as the Graduate Research Fellowship Program, to fund students pursuing QIST-related research.
  - To the extent possible, new QIST-related fellowships should include internships or other hands-on training experiences in QIST in industry or national laboratories.

- **Recommendation 8B: All previously authorized QIST education and training programs should be appropriated.**

  It is the opinion of the NQIAC that current U.S. STEM education pathways are leaving behind many Americans, including those from historically underrepresented demographic backgrounds, who could be a part of the future domestic QIST workforce. Efforts targeting all education levels, but particularly K-12 and community colleges, are necessary to make sure the future QIST workforce is more diverse and inclusive than the workforce of today. Investments in training, including up-skilling programs, at community colleges or vocational schools can have a near-term impact on the availability of technician-level talent that is needed for the growing QIST workforce. Education and outreach interventions at the K-12 level can increase overall awareness of QIST.

  To achieve these goals, legislation should appropriate all previously authorized QIST education and training programs, including the NSF Quantum Education Pilot Program authorized in the CHIPS and Science Act, as mentioned in Recommendation 1B.

- **Recommendation 8C: NSF should fund the development of a consolidated set of outreach programs, allowing QIST principal investigators to tap into these programs for their "broader impacts" on Federally-funded work for more cohesive and scalable impact.**

  In the long-term, as commercialized QIS technologies are adopted, not only will more QIST experts likely be needed, but also individuals with awareness of QIST. Currently, all NSF-funded research

[10] https://www.quantum.gov/wp-content/uploads/2022/01/Summary-QIS-Fed-Workforce-JAN2022.pdf

is required to incorporate an aspect of "broader impacts," which typically involves principal investigators developing education or outreach materials. The result is many independent efforts to create new web pages, lesson plans or other educational materials that may be duplicative or not well aligned with one another.

To make QIST outreach efforts more impactful, NSF should fund the creation of consolidated outreach programs. These programs can be developed by educational or outreach experts in close collaboration with QIST subject matter experts to employ approaches that work best for the various target populations.

- **Recommendation 8D: NSF should lead a holistic, systematic study of quantum workforce needs, trends, and education capacity. This study should be conducted and monitored biennially for the duration of the NQI to ensure U.S. leadership in QIST and competitiveness in the burgeoning quantum industry.**

  There is a gap in data on the current and future workforce needs of the QIST industry and the capacity of U.S. institutions to educate QIST talent. This information will be critical to effectively scope future investment in QIST education and workforce development programs. The NQIAC recommends a holistic, systematic study—with well-defined methodologies for data collection, such as that called for in the QIST Workforce Development National Strategic Plan—be expedited to inform decision making about future education and workforce development investments, thereby protecting against under- or over-supply of talent across degree fields and levels.

  Currently, collecting data about the QIST workforce is challenging as some job postings do not necessarily indicate they are quantum-related, even though they are. Similar challenges in data collection exist in degree programs, making it difficult to assess the current capacity of U.S. institutions of higher education to provide training in QIST. The role of technicians and other associate's degree-level workers in the future QIST industry is uncertain. Efforts such as CyberSeek,[11] which was created to map skill requirements and career pathways through the cybersecurity workforce, would be useful to replicate for the QIST workforce. For example, an assessment of the industry's need and requirements for QIST workers across degree levels, including QIST-specific master's degrees, certificates or credentials, and quantum engineering degrees, would inform the extent to which additional programs should be created and what their topical focus should be.

RECOMMENDATION 9: Employment of foreign talent in the U.S. QIST workforce should be facilitated and expedited through revised immigration policies and processes, thereby enhancing U.S. economic competitiveness and national security.

U.S. graduate schools attract talented students from all over the world to study QIST and related disciplines. At least half of all recent PhD recipients in QIST-relevant fields were temporary U.S. residents.[12] Yet, after graduation, U.S. immigration policy makes it difficult for these individuals to stay and work in the United States even though many wish to do so. At the same time, U.S. companies, universities, and laboratories are facing a significant shortage of trained QIST talent.

[11] https://www.cyberseek.org
[12] https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf

The United States could significantly expand the QIST workforce and increase its competitiveness by easing restrictions on staying to work in the United States by, among other measures,

- Expanding the number of employment-based visas for QIST positions.

- Increasing the number of slots for permanent residency based on educational qualifications (i.e., creating a STEM PhD Green Card classification).

- Relaxing country-specific quotas for Green Cards for QIST talent.

- Expediting immigration applications and petitions for QIST talent.

  For example, agencies should ensure that existing policies, such as those that could allow QIST workers to apply for a national interest waiver, are effective by improving training for adjudicators and ensuring timely adjudications are made.

- Permitting graduate students and postdoctoral fellows to apply for permanent residency early in their terms.

  Companies and U.S. Government laboratories seek applicants who can work on export-controlled QIST technologies, which excludes hiring students lacking citizenship or permanent residency status. Early consideration for permanent residency would decrease workforce shortages and accelerate progress.

The NQIAC believes that these changes could significantly enhance the number of foreign graduate students and postdoctoral fellows who would choose U.S. citizenship over other options. Such policies would benefit the economic and national security of the United States by avoiding the loss of STEM talent to foreign competitors or adversaries.

CONCLUSION

Renewing and augmenting the NQI will enable the United States to sustain its leadership in QIST discovery and innovation. The next phase of the NQI presents an opportunity to build on its science-first foundation to address key engineering and integration challenges that must be overcome to achieve applications with economic and societal benefits. These efforts require a whole-of-nation approach with participation from all sectors and cooperation with international partners. The NQIAC will continue to advise on opportunities for strengthening the NQI and ensuring U.S. leadership in QIST as activities proceed.