NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2022 BUDGET

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

December 2021

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development (R&D) enterprise. A primary objective of the NSTC is to ensure science and technology policy decisions and programs are consistent with the President's stated goals. The NSTC prepares R&D strategies that are coordinated across Federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at http://www.whitehouse.gov/ostp/nstc.

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The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS) was legislated by the National Quantum Initiative Act and coordinates Federal R&D in quantum information science and related technologies under the auspices of the NSTC Committee on Science. The aim of this R&D coordination is to maintain and expand U.S. leadership in quantum information science and its applications over the next decade.

About this Document

This document is a supplement to the President’s 2022 Budget request, and serves as the Annual Report for the National Quantum Initiative called for under the National Quantum Initiative Act.

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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARL	Army Research Laboratory
ARO	Army Research Office
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
HSST	House Committee on Science, Space, and Technology
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
IWG	Interagency Working Group
LPS	National Security Agency Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NQIAC	National Quantum Initiative Advisory Committee
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
QED-C	Quantum Economic Development Consortium
QLCI	Quantum Leap Challenge Institutes
R&D	research and development
SCQIS	Subcommittee on Quantum Information Science
USPTO	United States Patent and Trade Office
USDA	United States Department of Agriculture

Executive Summary

Quantum information science (QIS) unifies concepts from quantum mechanics and information theory, two foundational theories underpinning modern technology. QIS research includes transformative new types of computers, sensors, and networks that can improve the Nation's prosperity and security. Investment in fundamental QIS research thus lays a foundation for industries of the future, and opens new frontiers in science.

> *As new technologies continue to evolve, we'll work together with our democratic partners to ensure that new advances in areas from biotechnology, to quantum computing, 5G, artificial intelligence, and more are used to lift people up, to solve problems, and advance human freedom. – President Biden*[1]

The National Quantum Initiative (NQI) Act became Public Law 115-368 in December 2018 to accelerate American leadership in quantum information science and technology. The NQI Act authorizes U.S. Federal Departments and Agencies (hereafter, "agencies") to establish centers and consortia to foster QIS research and development (R&D). The NQI Act also calls for coordination of QIS R&D efforts across the Federal government, and with industry and the academic community.

This is the second Annual Report on the NQI Program budget, as required by the NQI Act. The release of this report follows a significant ramp-up of the NQI Program, with the establishment of several NQI centers and the Quantum Economic Development Consortium. Agencies reported actual budget authority for QIS R&D of $449 million in 2019 and $672 million in 2020, followed by $793 million of enacted budget authority for QIS R&D in FY 2021, and a requested budget authority of $877 million for QIS R&D in FY 2022.

The United States is investing in fundamental QIS R&D with core efforts underway in over a dozen agencies. To highlight the entire Federal QIS R&D enterprise, the substantial and sustained efforts funded by the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Defense (DOD), the Intelligence Community (IC), and the National Aeronautics and Space Administration (NASA) are recognized. This report includes brief summaries of agency efforts in addition to progress on cross-cutting QIS policy topics.

The strategic plan guiding NQI Program investments is the *National Strategic Overview for Quantum Information Science*. Released by the National Science and Technology Council (NSTC) Subcommittee on QIS in 2018, the *Strategic Overview* identifies policy areas discussed here in Section 4, namely: investing in fundamental science and engineering, developing the workforce capacity, engaging with industry, investing in infrastructure, maintaining economic and national security, and encouraging international cooperation.

Agency efforts in QIS R&D are growing because QIS can have profound and positive impacts on society and the way each agency accomplishes its mission. Furthermore, while the development of QIS technology is at an early stage, now is a critical time to develop infrastructure and fundamental scientific knowledge needed to grow the marketplace and foster new applications for QIS-inspired technology.

[1] https://www.whitehouse.gov/briefing-room/speeches-remarks/2021/09/21/remarks-by-president-biden-before-the-76th-session-of-the-united-nations-general-assembly/

1 Introduction

Quantum Information Science (QIS) builds on quantum mechanics and information theory to explore the fundamental limits for computation, networks, and measurement. The improved understanding of the quantum world provided by these explorations shows that, in some cases, the performance of quantum information systems can be vastly superior to that of traditional classical technologies. Building on key QIS discoveries since the 1980's, pioneering QIS experiments since the 1990's, growth in quantum engineering capabilities, and the development of several commercial activities underway now, the world is on the cusp of a second quantum revolution. The potential for innovations based on QIS and the associated implications for jobs and security motivated the United States to enact the National Quantum Initiative Act (NQI Act) and increase QIS education and training opportunities.

The NQI Act became law in 2018, "to provide for a coordinated Federal program to accelerate quantum R&D for the economic and national security of the United States."[2] The NQI Act authorizes NIST, NSF, and DOE to strengthen QIS Programs, Centers, and Consortia. The NQI Act also calls for a coordinated approach to QIS R&D efforts across the United States (U.S.) Government, including the civilian, defense, and intelligence sectors. To guide these actions, the NQI Act legislates several responsibilities for the NSTC Subcommittee on Quantum Information Science (SCQIS), the National Quantum Coordination Office (NQCO), and the National Quantum Initiative Advisory Committee (NQIAC). Concurrently, the Defense Quantum Information Science and Technology Research and Development Program, as legislated by the National Defense Authorization Act,[3] serves to continue DOD's three-decade history of basic QIS R&D. The NQI provides an overarching framework to strengthen and coordinate QIS R&D activities across agencies, private sector industry (see Figure 1), and the academic community.

Figure 1: Dr. Eric Lander, Presidential Science Advisor and Director of the Office of Science and Technology Policy, (center) participating in the White House Summit on Quantum Industry and Society,[4] along with Dr. Jason Matheny, Deputy Assistant to the President for Technology and National Security, Deputy Director for National Security in the Office of Science and Technology Policy, and Coordinator for Technology and National Security at the National Security Council (to Dr. Lander's right).

[2] https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[3] https://www.congress.gov/115/plaws/publ232/PLAW-115publ232.pdf; https://www.congress.gov/116/plaws/publ92/PLAW-116publ92.pdf
[4] https://www.whitehouse.gov/ostp/news-updates/2021/10/07/readout-of-white-house-summit-on-quantum-industry-and-society/

The *National Strategic Overview for QIS*[5] recommends strengthening the United States' approach to QIS R&D, by focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation. Key activities and the Federal budgets used to support them are reported here. For example, NIST formed the Quantum Economic Development Consortium (QED-C), NSF announced Quantum Leap Challenges Institutes (QLCI), and DOE established its National QIS Research Centers. Mechanisms to strengthen core programs and coordinate QIS R&D efforts across the Federal government are also described here.

The SCQIS, NQIAC, and NQCO are legislated by the NQI Act.[2] Their activities build on Federal QIS R&D coordination via interagency activities such as those described in the 2009 NSTC Report on *A Federal Vision for QIS*[7] and the 2016 NSTC Report from the Interagency Working Group on QIS.[8] U.S. QIS R&D efforts are also informed by numerous federally-funded workshops led by the QIS R&D community.[9]

Box 1.1

COORDINATING BODIES SUPPORTING THE NATIONAL QUANTUM INITIATIVE

The Subcommittee on Quantum Information Science (SCQIS) of the NSTC coordinates Federal R&D in quantum information science and technology under the auspices of the NSTC Committee on Science. The SCQIS is co-chaired by OSTP, the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF) and the Department of Energy (DOE). Interagency discussions and recommendations by the SCQIS aim to strengthen U.S. leadership in quantum information science and its applications over the next decade. Members of the SCQIS are listed in the front matter of this document.

The Subcommittee on Economic and Security Implications of Quantum Sciences (ESIX) of the NSTC is co-chaired by the Department of Defense (DOD), the National Security Agency (NSA), DOE, and OSTP. In parallel with SCQIS, the ESIX Subcommittee works to ensure that the economic and security implications of QIS are understood across the agencies, while providing a national security perspective to QIS related research policy.

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal advisory committee called for in the NQI Act to counsel the administration on ways to ensure continued American leadership in QIS. The NQIAC is tasked to provide an independent assessment of the NQI Program and to make recommendations to the President and the Subcommittees to consider when reviewing and revising the NQI Program. The NQIAC consists of leaders in the field from industry, academia and the Federal government.

The National Quantum Coordination Office (NQCO) is located in OSTP within the Executive Office of the President to carry out daily activities needed for coordinating and supporting the NQI Program. The NQCO is tasked with providing technical and administrative support to the SCQIS and the NQIAC, overseeing interagency coordination of the NQI Program, serving as the point of contact on Federal civilian QIS and technology activities, ensuring coordination among the consortia and various quantum centers, and conducting public outreach. The NQCO staff consists of Federal employees on detail assignments from across the government.

[5] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[6] https://www.nist.gov/blogs/taking-measure/your-qubit-better-my-qubit
[7] https://www.quantum.gov/wp-content/uploads/2020/10/2009_NSTC_Federal_Vision_QIS.pdf
[8] https://www.quantum.gov/wp-content/uploads/2020/10/2016_NSTC_Advancing_QIS.pdf
[9] https://www.quantum.gov/publications-and-resources/publication-library/

2 Budget Data

U.S. Federal budgets for QIS R&D presented here summarize Fiscal Years (FY) 2019 and 2020 actual expenditures, FY 2021 estimated expenditures, and FY 2022 requested budgets. U.S. QIS R&D Budgets are on track to roughly double by FY 2022 as compared to FY 2019, with efforts catalyzed by the NQI Program. QIS R&D is also called for in the Multi-Agency R&D Priorities Memo for the FY 2023 Budget.[10]

Figure 2.1 shows overall Federal budgets for U.S. QIS R&D activities aggregated across several agencies (NIST, NSF, DOE, DHS, DOD, and NASA), and aggregated across several QIS subtopics (e.g., computing, networking, sensing, fundamental science, and technologies). Much of the growth in QIS R&D budgets is for NQI activities such as the establishment of quantum consortia by NIST, Quantum Leap Challenge Institutes (QLCI) by NSF, National QIS Research Centers by DOE, and coordination and strengthening of core QIS programs across many agencies. Sustained growth in U.S. QIS R&D will position American universities, industries, and government researchers to explore quantum frontiers, advance QIS technologies, and develop the required workforce to continue American leadership in this field and related industries of the future.

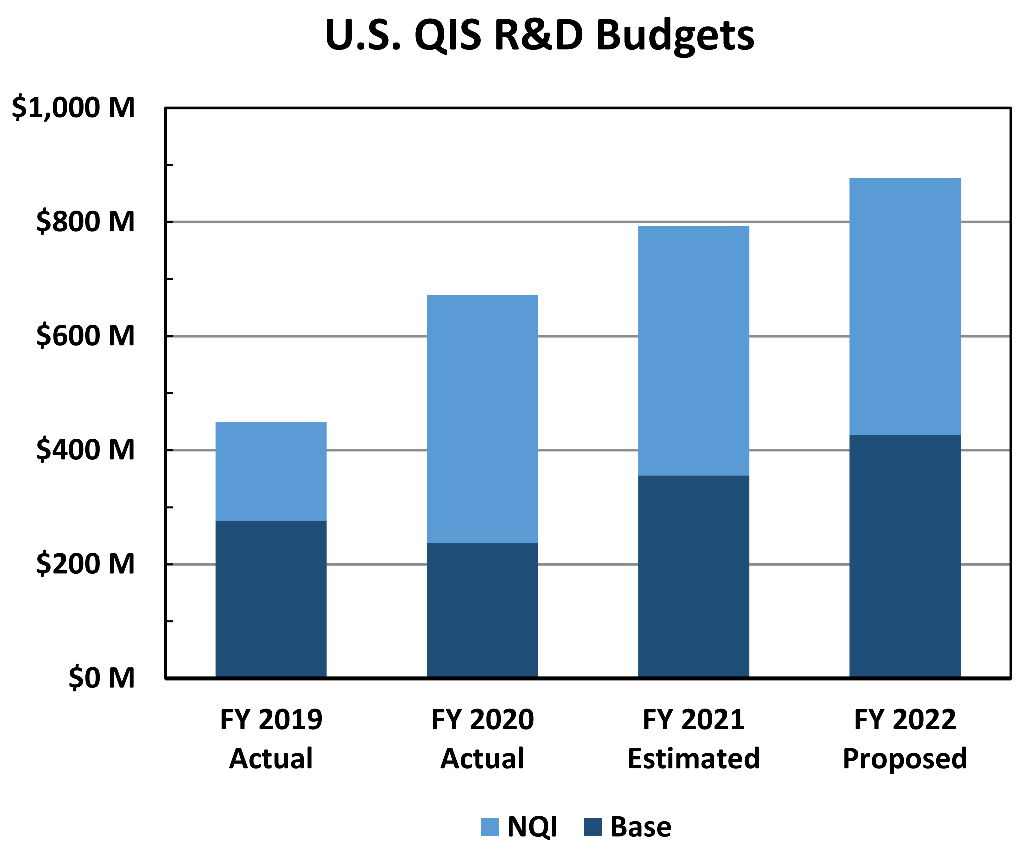

Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQI Act. The bar heights represent the total budget for each fiscal year (FY 2019 & FY 2020 actual expenditures, FY 2021 estimated expenditures, and FY 2022 requested budgets). The portion of each bar marked "NQI" identifies funding allocated for NQI Act-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities.

[10] https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21-32-Multi-Agency-Research-and-Development-Prioirties-for-FY-2023-Budget-.pdf

Budget distributions over five different NQI Program Component Areas, or PCAs, are discussed next. These PCAs are used by the Office of Management and Budget (OMB) to collect and analyze budget data, and are consistent with the classification introduced in the *National Strategic Overview for QIS* and used in the first Annual Report on the NQI Program.

NQI Program Component Areas

- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. This can include uses of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by quantum control, for example with atomic clocks.
- **Quantum Computing (QCOMP)** activities include the development of quantum bits (qubits) and entangling gates, quantum algorithms and software, digital and analog quantum simulators using programmable quantum devices, quantum computers and prototypes, and hybrid digital plus analog, as well as quantum plus classical computing systems.
- **Quantum Networking (QNET)** includes efforts to create and use entangled quantum states, distributed over distances and shared by multiple parties, for new information technology applications and fundamental science; for example, networking of intermediate scale quantum computers (modules) for enhanced beyond-classical computing capabilities.
- **QIS for Advancing Fundamental Science (QADV)** includes foundational efforts to invoke quantum devices and QIS theory to expand fundamental knowledge in other disciplines; for example, to improve understanding of biology, chemistry, computation, cosmology, energy science, engineering, materials, nuclear matter, and other aspects of fundamental science.
- **Quantum Technology (QT)** catalogues several topics: work with end-users to deploy quantum technologies in the field and develop use cases; basic R&D on supporting technology for quantum information science and engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography (see Box 4.1).

Figure 2.2 shows budget allocations by NQI Program Component Area (PCA) for FY 2019-2022 using a “layer-cake” bar chart for each year. A final breakdown for the budget data presented here shows QIS R&D budgets by agency. Figure 2.3 shows the total QIS R&D budgets for the three agencies prominently identified in the NQI Act: NIST, NSF, and DOE.

In summary, the budget charts show U.S. Government investments in QIS R&D. Respectively, Figures 2.1-2.3 present budget portions for NQI-Act-authorized activities, NQI PCAs, and selected agencies. The data show an increased investment in QIS R&D across the Federal government, and across each PCA, in alignment with each agency’s mission and a coordinated Federal program to accelerate quantum R&D. The budget data were provided by agencies directly to OMB as part of a routine QIS crosscut reporting process, to enable coordinated monitoring and implementation of the NQI Program.

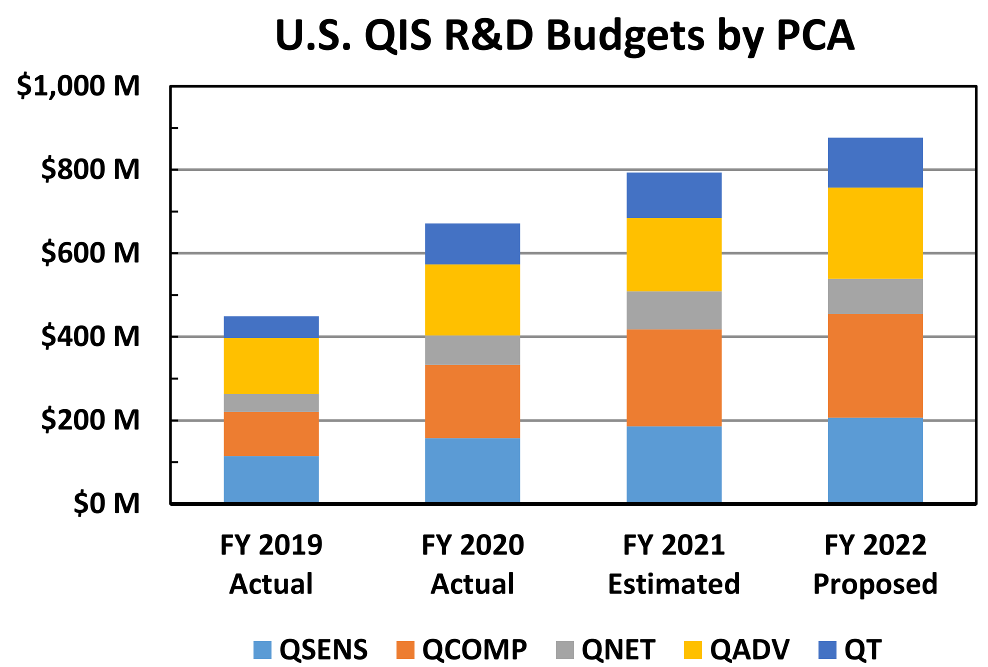

Figure 2.2: U.S. QIS R&D Budget allocations by NQI Program Component Area (PCA) topic for FY 2019 & FY 2020 actual expenditures, FY 2021 estimated expenditures, and FY 2022 requested budgets.

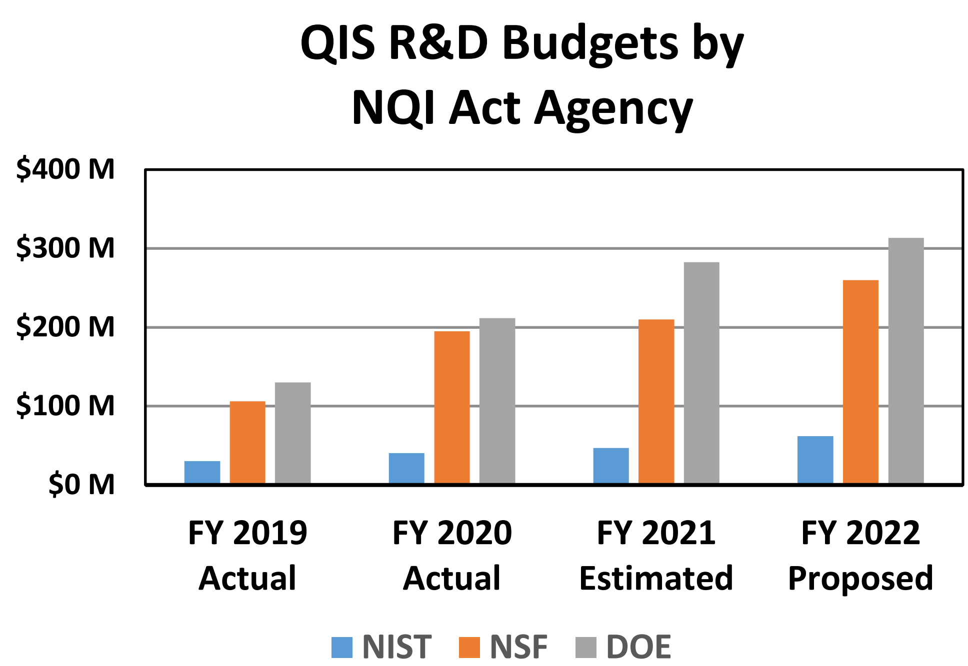

Figure 2.3: QIS R&D Budgets for three Agencies identified in the NQI Act, showing FY 2019 & FY 2020 actual expenditures, FY 2021 estimated expenditures, and FY 2022 requested budgets.

The next sections describe how agencies are using these budgets to advance quantum information science and engineering (QISE) R&D. The added emphasis on engineering, as called for by the NQI Act, recognizes the increasingly important role of system design and component manufacturing to accelerate QIS discoveries and their translation into technologies and applications that address agency missions and various industrial and societal needs.

As stated in the introduction, the National Quantum Initiative provides a framework to strengthen and coordinate QIS R&D activities across federal agencies. The NQI also promotes engagements with the private sector industry, the academic community, National Laboratories, and Federally Funded Research and Development Centers (FFRDCs). Reinforcing and synergistic investments in fundamental quantum information science, basic QIST research, education, training, and workforce development, collectively unite agencies' efforts with a kind of structure suggested in Figure 2.4. The resulting ecosystem accelerates American leadership in QIST by simultaneously promoting discovery, exploration, and efforts to develop the market, supply chain, infrastructure, and capacity to utilize quantum technologies.

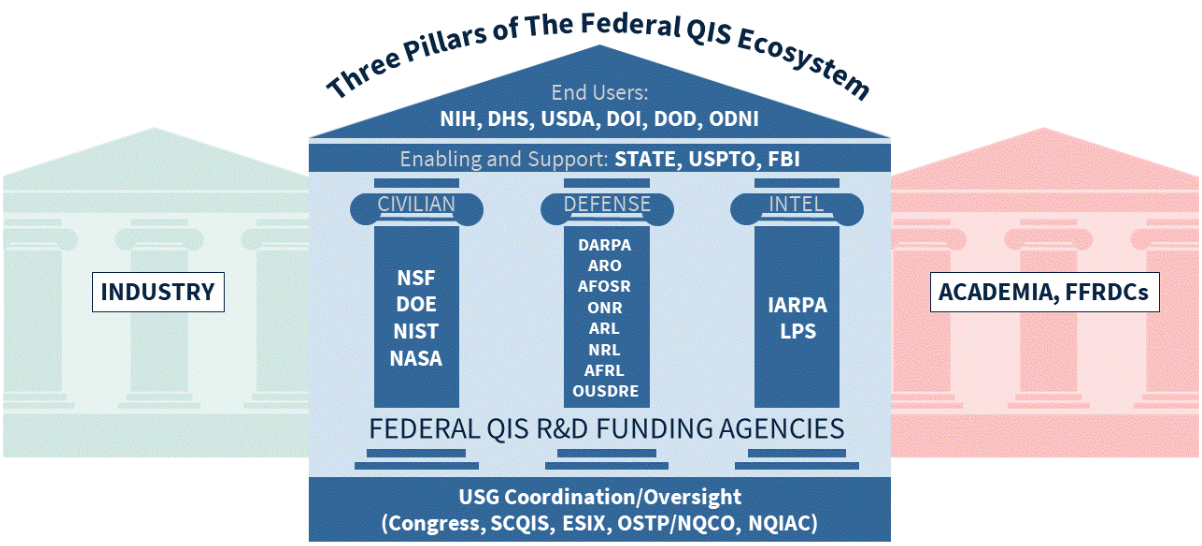

Figure 2.4: Federal QIS R&D funding agencies can be seen as three pillars that support the Federal QIS ecosystem. Civilian science agencies (NSF, DOE, NIST, NASA) stand alongside the Department of Defense science agencies [DARPA, ARO, AFOSR, ONR, ARL, NRL, AFRL, OUSD(R&E)] and the Intelligence Community science agencies (IARPA, LPS) to collectively support QIS R&D efforts. Within Federal government, administrative support enabling the QIS ecosystem also comes from FBI, USPTO and DOS, and potential end users including NIH, DHS, USDA, DOI, DOD, and ODNI. Authorization, coordination and oversight are provided by Congress, SCQIS, ESIX, OSTP, NQCO, and NQIAC. Pictured here as separate houses, Industry, Academia, and Federally Funded Research and Development Centers (FFRDC's) are also critically important for QIS R&D.

Next, Section 3 summarizes QIS R&D programs at selected agencies. Then Section 4 tracks progress on key policy topics identified in the *National Strategic Overview for QIS*.

3 QIS R&D Program Highlights

This section describes QIS R&D activities by agency, starting with NIST, NSF and DOE because these three agencies have particular responsibilities authorized by the NQI Act. Then QIS efforts at DOD, NASA, LPS, and IARPA are described, to provide a more complete description of the U.S. QIS R&D enterprise. Each agency works independently on their respective missions. Yet the collection of efforts is crucial for American leadership in QIS. Coordinated with coherent policy goals, the combined set of activities described here accelerates basic science, exploration, and the development of new technologies.

Featured throughout this section are QIS R&D highlights, selected to illustrate the range of discovery and technical achievement by agency programs. In many cases the results are fueled by support from multiple agencies, e.g. Boxes 3.1, 3.3, 3.5, 3.7, 3.9, and 3.11.

Box 3.1

Quantum Sensing Highlight

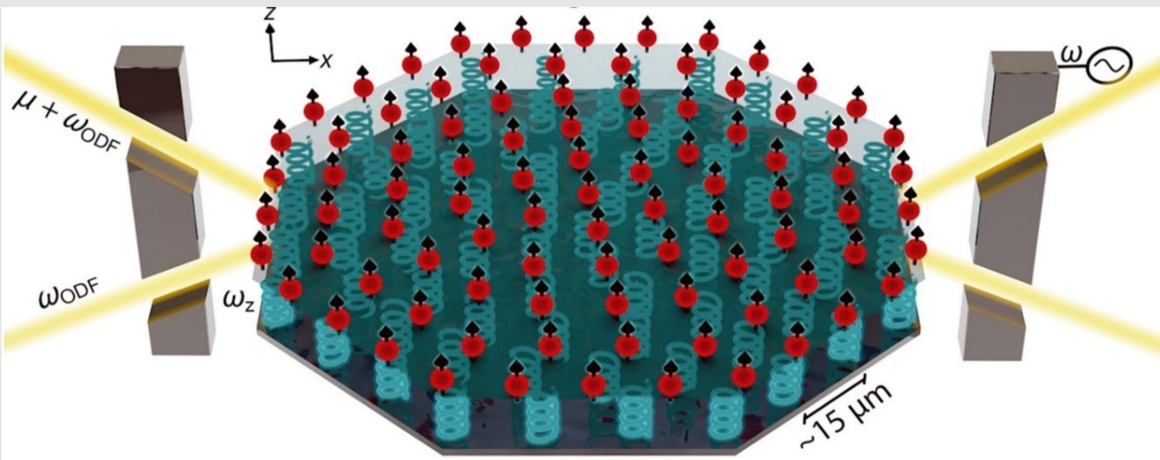

Figure 3.1: A crystal of trapped ions, depicted as mechanical oscillators with spins, was manipulated with lasers (yellow beams) to create metrologically useful entanglement, and measure electric fields with better sensitivity than classical technology.

Using entanglement, scientists at NIST and the University of Colorado demonstrated a quantum advantage for measuring electric fields.[11,12] They entangled the center of mass motion and the collective spin for a crystal of trapped ions - two quantum mechanical degrees of freedom for a many-body system - using pairs of laser beams as represented in Fig. 3.1. A sophisticated sequence of quantum state preparation, manipulation, and detection produced metrologically useful entanglement, without the deleterious effects of quantum back-action or heating. The resulting enhancement in sensitivity to ion displacement and electric fields can improve sensors for elementary particle physics, signal detection, and metrology for time and frequency.

The experiment, conducted at NIST, also leveraged collaborations with a DOE National QIS Research Center, an NSF Quantum Leap Challenge Institute, an NSF Physics Frontiers Center, and teams supported by the DOE QuantISED program, two AFOSR awards, the DARPA ONISQ program, and awards from core NSF and ARO programs. These QIS programs, highlighted throughout this report, function together to accelerate the exploration of quantum sensors that will offer new modalities for measurement, with enhanced precision and accuracy compared to classical technologies.

[11] https://www.nist.gov/news-events/news/2021/08/nists-quantum-crystal-could-be-new-dark-matter-sensor
[12] https://www.science.org/lookup/doi/10.1126/science.abi5226

3.1 The National Institute of Standards and Technology (NIST)

NIST promotes U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. With emphasis on precision metrology and cybersecurity, NIST conducts open, world-class research touching all elements of the National QIS agenda.[13] NIST has been a leader in QIS R&D for over three decades, including a seminal workshop on QIS at its Gaithersburg campus in 1994, and ongoing quantum activities at NIST highlighted at https://www.nist.gov/topics/quantum-information-science. As authorized by the NQI Act, NIST is coordinating consortia focusing on quantum technologies and the prerequisite supply chains, while maintaining its fundamental QIS R&D programs. The FY 2022 budget request for NIST includes a funding request to "expand the quantum network testbed program, grow the Quantum Economic Development Consortium and increase joint institute partnerships".[14]

QIS R&D activities supported by NIST include:

- NIST initiated the formation of the Quantum Economic Development Consortium (QED-C)[15] using its Other Transaction Authority in collaboration with SRI International, to extend U.S. leadership in quantum research by building the future supply chain needed for the quantum economy. This year, the QED-C formally moved to a membership model, with over 150 entities signing a participation agreement. NIST has been working closely with members of the QED-C to engage with the International Telecommunication Union agency of the United Nations around quantum communication and computing and with IEEE around broader quantum technologies and quantum benchmarking. The QED-C is providing useful perspectives on the importance and readiness levels of standards activities in QIS. The State Department has been very helpful in the engagement with ITU. See Box 3.2 on the QED-C.
- NIST engages with industry through Cooperative Research and Development Agreements (CRADAs) that facilitate access to NIST laboratories and the transfer of technology.
- NIST's Center for Nanoscale Science and Technology (CNST) is a national user facility in which many types of QIS devices may be prototyped. NIST's Boulder microfabrication facility is a leading facility for superconducting devices and integrated photonics.
- NIST works collaboratively with its peer National Metrology Institutes around the world on quantum metrology, including methods for dissemination of the International System of Units, or SI. Recently, NIST published the most accurate optical frequency ratio measurements performed to date, making a significant step in the roadmap for redefining the second in the SI.
- NIST's joint institutes—JILA (with the University of Colorado/Boulder) and the Joint Quantum Institute, or JQI, and the Joint Center for Quantum Information and Computer Science, or QUICS, (with the University of Maryland at College Park)—provide QIS instruction and research opportunities to undergraduate and graduate students. A long history of collaboration with, and substantial and sustained sponsorship by, NSF, DOD, and the IC has enhanced research activities at NIST and at its joint institutes.
- The NRC Postdoctoral and JILA Visiting Fellows programs provide additional opportunities for transformative post-graduate and early-career experiences.

[13] https://www.nist.gov/topics/quantum-information-science
[14] https://www.nist.gov/director/congressional-and-legislative-affairs/nist-appropriations-summary-0/fy-2022-presidential
[15] https://quantumconsortium.org/

- NIST initiated an effort to design a prototype compact optical atomic clock that would have a sufficient holdover time to provide a backup to GPS for up to two weeks. The focus is to have a power requirement on the order of 100 watts and a size of a few liters. Such a clock, if made and appropriately priced, could be placed on cell phone towers and internet switching stations.
- NIST established a program on building a scalable quantum repeater using ion trap technology to support the numerous efforts to build a general-purpose quantum network. Two missing technologies for such a network are quantum memory and a quantum repeater.
- The NIST-led process for Post-Quantum Cryptography (PQC) Standards is in the final selection round. This activity is crucial to secure our public key infrastructure once a general-purpose quantum computer becomes available.[16] See the Box 4.1 on PQC (in Section 4.5).
    - In June, NIST held a third NIST PQC Standardization Conference to discuss various aspects of these candidates, and to obtain valuable feedback for the final selection(s). NIST invited each submission team of the 15 finalists and alternates to give a short update on their algorithm.
    - To support this activity, NIST released the final version of its 'Getting Ready for Post Quantum Cryptography',[17] a whitepaper on the Challenges with Adopting Post-Quantum Cryptographic Algorithms,[18] and a blog post titled, 'The Future Is Now: Spreading the Word About Post-Quantum Cryptography'.[19]

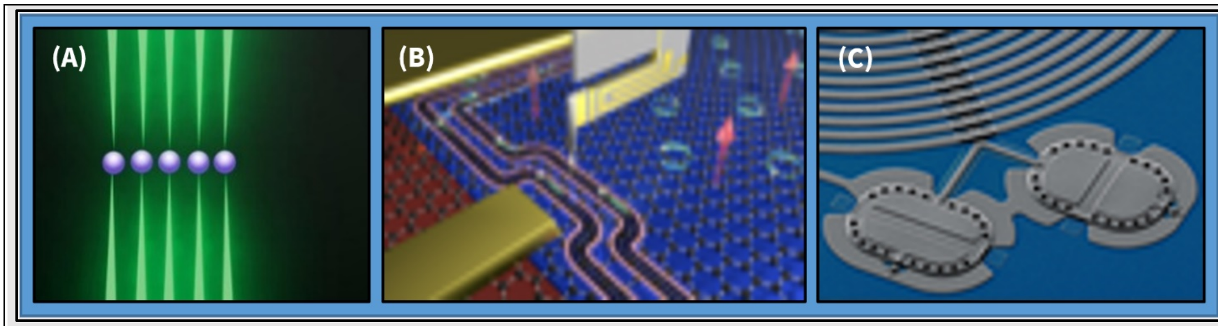

Figure 3.2: Examples of QIS R&D at NIST. (A) depiction of cold atoms in optical tweezers.[20] (B) device for imaging quantum Hall edges. [23] (C) apparatus for entangling mechanical drum heads.[24]

NIST QIS R&D activities highlighted in the news:

- (December 16, 2020) NIST demonstrated new ultra-stable optical atomic clock technology based on cold atoms in optical tweezer arrays (see Fig. 3.2A).[20]
- (March 24, 2021) NIST compared three leading optical atomic clocks via both free-space and optical-fiber links, demonstrating record accuracy from NIST quantum technology being developed for the future international redefinition of the second.[21]

[16] https://www.nist.gov/news-events/news/2020/07/nists-post-quantum-cryptography-program-enters-selection-round
[17] https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.04282021.pdf
[18] https://www.quantum.gov/nist-releases-whitepaper-on-the-challenges-with-adopting-post-quantum-cryptographic-algorithms/
[19] https://www.nist.gov/blogs/taking-measure/future-now-spreading-word-about-post-quantum-cryptography
[20] https://www.nist.gov/news-events/news/2020/12/jilas-bigger-and-better-tweezer-clock-super-stable
[21] https://www.nist.gov/news-events/news/2021/03/nist-team-compares-3-top-atomic-clocks-record-accuracy-over-both-fiber-and

- (March 24, 2021) NIST demonstrated readout and control of a superconducting qubit over a photonic (fiber optic) link, opening a path to reducing the input cabling requirements necessary for large-scale quantum computing.[22]
- (May 14, 2021) NIST researchers have taken the first ever images of Quantum Hall (QH) edge states and examined their underlying structure and size. The persistence of QH edge states makes them potential candidates for quantum bits or qubits (see Fig. 3.2B).[23]
- (May 06, 2021) NIST researchers have entangled two small mechanical drums and precisely measured their linked quantum properties. Entangled pairs like this might someday perform computations and transmit data in large-scale quantum networks (see Fig. 3.2C).[24]

Box 3.2

Quantum Economic Development Consortium: The QED-C is an industry-led consortium that aims to extend U.S. leadership in quantum research by building supply chains for the quantum economy. QED-C membership includes over 150 companies, non-profits, and academic institutions that have signed participation agreements. A list of members can be found at the QED-C webpage.[25]

The QED-C convenes members to work on cross-cutting issues for technology and workforce development, and to collaborate in a pre-competitive space to move the entire industry forward. Federal agencies, including NIST, DOE, and DOD engage with the QED-C by participating in meetings, workshops, and Technical Advisory Committees (TACs). QED-C TACs and their goals include:

TAC on Enabling Technologies: Identify enabling technologies – both quantum and classical – that need to be advanced to realize high economic impact applications and uses.

TAC on Q4NS: Create a forum for government and industry to exchange information related to advancing QIST for national security applications. Topics cross-cut with other TACs, but with a national security focus.

TAC on Quantum Law: Create a forum for government, industry and academia to exchange information about legal and legal-adjacent issues and policies related to QIST. Topics of interest include international engagement, workforce diversity, intellectual property and social/ethical matters of QIST applications.

TAC on Standards and Performance Metrics: Identify standards and metrics that can accelerate commercialization of quantum-based products and services. Connect members with relevant standards development organizations worldwide.

TAC on Use Cases: Identify and elaborate applications and use cases of quantum-enabled technologies. The output will inform companies across the supply chain — from component suppliers to users — as well as policy makers, government program managers, and investors.

TAC on Workforce: Identify education and workforce development needs to support the emerging quantum industry, working with universities and other educational institutions.

[22] https://www.nist.gov/news-events/news/2021/03/optical-fiber-could-boost-power-superconducting-quantum-computers
[23] https://www.nist.gov/news-events/news/2021/05/nist-team-probes-indestructible-quantum-states-may-aid-quantum-computing
[24] https://www.nist.gov/news-events/news/2021/05/nist-team-directs-and-measures-quantum-drum-duet
[25] https://quantumconsortium.org/members/

Box 3.3

Qubit Testbed Highlight

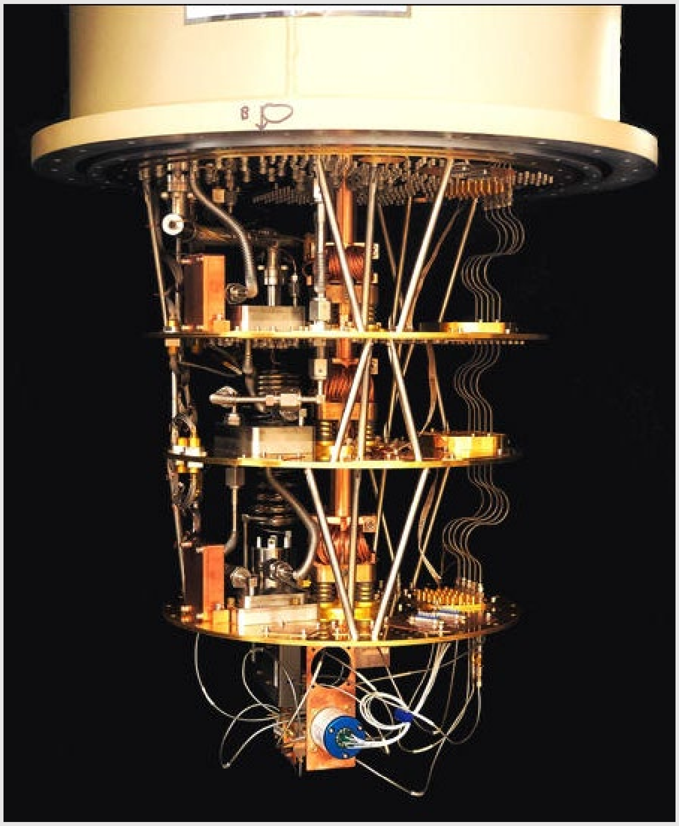

Figure 3.3 The Boulder Cryogenic Qubit Testbed. Credit: H. Wang, NIST

- (January 09, 2021) NIST researchers have developed a new ion trap with a component that could be key to streamlining the construction of huge quantum computers: a built-in single-photon detector.[26]
- (February 10, 2021) The Boulder cryogenic qubit testbed for benchmarking qubits is a joint effort with government, private sector, and academic engagement.[27] It's housed in JILA on the CU Boulder campus and will serve researchers from across the country working to design the latest superconducting quantum circuits.[28] It addresses the growing need for benchmark tests, standards, and certification for dielectric material and qubit components for quantum computing. This adds to the growing toolkit for qubit and quantum information processing system verification, validation, and characterization. See, for example, the workshop on Assessing Performance of Quantum Computers[29] and the IEEE workshop on Benchmarking Quantum Computational Devices and Systems.[30]
- (April 12, 2021) NIST researchers take counting single photons to an unprecedented rate.[31]

[26] https://www.nist.gov/news-events/news/2021/01/spotlight-new-ion-trap-single-photon-detector
[27] https://www.nist.gov/blogs/taking-measure/your-qubit-better-my-qubit
[28] https://www.colorado.edu/today/2019/10/03/new-boulder-facility-help-pave-way-quantum-computers
[29] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1931779
[30] https://quantum.ieee.org/education/quantum-supremacy-and-quantum-computer-performance
[31] https://www.quantum.gov/nist-researchers-take-counting-single-photons-to-an-unprecedented-rate/

3.2 The National Science Foundation (NSF)

NSF promotes the progress of science by funding basic research at approximately 2000 academic institutions throughout the United States. The NQI Act authorizes NSF to strengthen core programs and establish new multidisciplinary Centers for QISE research and education. Implementation of these activities is ongoing with a myriad of efforts listed on www.nsf.gov/quantum,[32] many of which build upon NSF's Quantum Leap Big Idea.[33] NSF's FY 2022 budget request to Congress has a section on QIS[34] that articulates three goals guiding NSF investments in QISE research: (1) "Answer key science and engineering questions in order to facilitate the fundamental understanding of quantum phenomena and systems, as well as the translation of that fundamental knowledge into technological applications"; (2) "Deliver proof-of-concept devices, applications, tools, or systems with a demonstrable quantum advantage over their classical counterparts that will form the basis of a revolutionary 21st-century technology"; and (3) "Empower the full spectrum of talent to which NSF has access, to build the capacity necessary to achieve goals (1) and (2) and generate the quantum-literate workforce that will implement the results of these breakthroughs."

QISE R&D Programs at NSF:

- Quantum Leap Challenge Institutes (QLCI) are NSF's flagship multidisciplinary Centers for QISE research and education. The QLCI Program[35] supports large-scale efforts on scientific, technological, and workforce development challenges related to quantum computation, quantum communication, quantum simulation, and quantum sensing. See Box 3.4 on QLCI Institutes.
- Transformational Advances in Quantum Systems (TAQS) solicitations are opportunities for interdisciplinary teams to grow the QIS R&D community. These include the Quantum Interconnects (QuIC-TAQS) Solicitation NSF 21-553, the Quantum Idea Incubator (QII-TAQS) Solicitation NSF 19-532, and the pilot TAQS opportunity NSF 18-035. See TAQS Awards.[36]
- The Quantum Leap at NSF enabled workshops and efforts such as TAQS and the Quantum Algorithm Challenge,[37] which laid foundations for NQI Program activities.
- Core programs at NSF support fundamental QIS research and training. A list of seventeen core programs with connections to QIS, from three NSF Directorates, is online.[38]
- Other large-scale QISE efforts include the Center for Quantum Information and Control (CQUIC) at the University of New Mexico, the NSF Engineering Research Center for Quantum Networks (CQN) at the University of Arizona, the NSF Quantum Foundry at the University of California, Santa Barbara, the NSF Quantum Foundry shared between Montana State University and the University of Arkansas, the Joint Quantum Institute (JQI) at University of Maryland, the Institute for Quantum Information and Matter (IQIM) at the California Institute of Technology, the MIT-Harvard Center for Ultracold Atoms (CUA), JILA at the University of Colorado Boulder, the Center for Integrated Quantum Materials (CIQM) at Harvard University, the multi-institutional Software-Tailored Architecture for Quantum co-design (STAQ) project at Duke University, the multi-institutional Enabling Practical-Scale Quantum Computing (EPiQC) project, the multi-campus research and

[32] https://www.nsf.gov/mps/quantum/quantum_research_at_nsf.jsp
[33] https://www.nsf.gov/news/special_reports/big_ideas/quantum.jsp
[34] https://www.nsf.gov/about/budget/fy2022/pdf/29_fy2022.pdf; https://www.nsf.gov/about/budget/fy2022/toc.jsp
[35] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505634
[36] https://www.nsf.gov/awardsearch/simpleSearchResult?queryText=TAQS&ActiveAwards=true
[37] https://www.nsf.gov/pubs/2020/nsf20056/nsf20056.jsp?org=NSF; for QAC Awards see https://www.nsf.gov/quantum
[38] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505283

education cluster on Emergent Quantum Materials and Technologies (EQUATE) led by the University of Nebraska, and the Materials Science and Engineering Center (MRSEC) projects focused on quantum technologies such as the Princeton Center for Complex Materials, the Columbia Center for Precision-Assembled Quantum Materials (PAQM), and the Penn State University Center for Nanoscale Science, and the National Nanotechnology Coordinated Infrastructure (NNCI) program.

NSF QIS R&D activities highlighted in the news:

- NSF announced $9.75 million for Quantum Computing Faculty Fellows to stimulate universities to create more QIS faculty jobs in computer science departments with interdisciplinary research and curricula.[39] Thirteen faculty fellow positions have been funded through this program.[40]
- A series of Quantum Engineering workshops in FY 2021 included:
    - NSF Workshop on Quantum Engineering Education[41]
    - NSF/NNCI Workshop on Quantum Engineering Infrastructure[42]
    - NSF Workshop on Quantum Devices & Systems Manufacturing[43]
    - Emerging Opportunities at the Intersection of Quantum and Thermal Sciences[44]
- In 2020, NSF established the Q2Work Program to support QIS educators and learners.[45,46] NSF also outlined mechanisms to support the development of educational approaches for pre-college students' computational skills and interest in QIS.[47]
- In 2021, NSF added QIS to the National Science Foundation Research Traineeship (NRT) program as a priority area of emphasis in which the program encourages submission of proposals.
- In 2021, the NSF Directorate for Education and Human Resources (EHR) issued a Letter, "Advancing Quantum Education and Workforce Development" and presented Webinars to highlight twenty NSF Programs that welcome proposals to help students at all levels develop QISE interests.[48,49]
- Engagement with QIS industry is supported by several NSF mechanisms including:
    - GOALI and I-CORPS programs;
    - Ten Convergence Accelerator Awards for Quantum Technology (NSF 20-565 Track C);
    - The IUCRC program QISE workshop and Planning Grants;[50]
    - The "Triplets program" for QISE-Net activities;[51] and
    - The "Enabling Quantum Computing Platform Access" Dear Colleague Letter (NSF 20-073), which states, "NSF and Amazon Web Services, IBM, and Microsoft Quantum are

[39] https://www.nsf.gov/news/news_summ.jsp?cntn_id=301001&org=CISE
[40] https://www.nsf.gov/awardsearch/simpleSearchResult?queryText=%22QCIS-FF%22
[41] https://quantum.mines.edu/nsf-qe-ed/
[42] https://www.cnf.cornell.edu/events/nsf-nnci-quantum;
[43] https://sites.duke.edu/qdsworkshop/
[44] https://cvent.utexas.edu/2021NSF-QTSW
[45] https://www.nsf.gov\news\special_reports\announcements\080520.jsp
[46] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2039745&HistoricalAwards=false
[47] https://www.nsf.gov/pubs/2020/nsf20101/nsf20101.jsp
[48] https://www.nsf.gov/pubs/2021/nsf21033/nsf21033.jsp
[49] https://www.quantumdcl.edc.org/april_27th.html
[50] https://uidp.org/publication/catalyzing-industry-university-collaboration-in-quantum-technologies-workshop-report/; and NSF Awards 2052730, 2052661, 2052739, 2052706
[51] See NSF Award 1747426 and https://qisenet.uchicago.edu/

coordinating to make available cloud-based quantum-computing platforms to advance research and build capacity in the academic setting."

- International cooperation on QIS research and skills training is supported through collaboration with NSF projects. See, for example, DCL NSF 21-090 for "International Collaboration Supplements in Quantum Information Science and Engineering Research."
- A series of NSF workshops on scientific and community needs, opportunities, and challenges in QISE resulted in several strategy documents developed by academic, national laboratory, and industrial researchers, including:
  - Quantum Computer Systems for Scientific Discovery[52]
  - Quantum Simulators: Architectures and Opportunities[53]
  - Development of Quantum Interconnects for Next-Generation Information Technologies[54]

Box 3.4

Quantum Leap Challenge Institutes: Five QLCI Institutes established by NSF cover a wide range of QISE topics including sensing, networks, computing, simulators, biophysics, and engineering.

Q-SEnSE · The Quantum Systems through Entangled Science and Engineering QLCI research efforts are built around three grand challenges: (1) Ultra-precise sensing and measurement with a quantum advantage in order to integrate, package, and produce practical, functioning systems that can be tested and reliably deployed in the field, (2) Engineering principles applied to quantum information science, and (3) National infrastructure for applications in quantum sensing to design reliable, standardized quantum components with well characterized performance metrics and ready them for transition to Industry.[55]

HQAN · The Hybrid Quantum Architectures and Networks QLCI research efforts are built around three major activities: (1) Developing multi-node heterogeneous networks based on proven technologies with the capacity for distributed processing, (2) developing a distributed computing software stack, multi-node information protocols, and new use-cases that are optimized for these hybrid networks, and (3) creating next-generation protected qubits with enhanced performance and integrating these devices into the center testbeds.[56]

CIQC · The Challenge Institute for Quantum Computation research efforts are built around three fundamental challenges to the development of the quantum computer: (1) Quantum algorithms – this thrust aims to clarify the advantages that quantum information processing (QIP) holds over classical computation, both as a fundamental question of complexity and resources, and also for practical application, (2) Verifiable quantum advantage - which aims to verify advantages for quantum computers over classical ones, within an expanding range of computing platforms and computational tasks, and (3) Scaling quantum systems - which has the specific aim of utilizing AMO-based quantum technologies, including advances in optical engineering, to realize improved modularity, high-fidelity operation and classical control within quantum systems of increasing size and complexity, deriving generalized approaches to scaling up QIP.[57]

[52] https://doi.org/10.1103/PRXQuantum.2.017001
[53] https://doi.org/10.1103/PRXQuantum.2.017003
[54] https://doi.org/10.1103/PRXQuantum.2.017002
[55] https://www.colorado.edu/research/qsense/
[56] https://hqan.illinois.edu/
[57] https://ciqc.berkeley.edu/

QuBBE · The Quantum Sensing for Biophysics and Bioengineering QLCI research efforts seek to create quantum imagining and measurement systems that exceed what can be done with classical technologies for studies of biology. Combining expertise in chemistry, physics, molecular engineering, medicine, and cellular biology, QuBBE research teams are focused on exploiting quantum coherence and correlations to probe structure, dynamics, and function in vivo. In addition to sensing systems, studies of in vivo coherence, and correlation imaging, and biomedical science, this QLCI Institute will advance curricular and outreach efforts with a quantum academy.[58]

RQS · The Robust Quantum Simulation QLCI will use quantum simulators to gain insight into the rich behavior of complex quantum systems and address outstanding research questions in scientific disciplines such as nuclear and high-energy physics, chemistry and materials, and computer science. RQS researchers will develop methods to verify and certify the correctness of quantum simulations, to assess trustworthiness even when they are classically intractable. Quantum error correction will be explored as a physical phenomenon, using statistical mechanics to study interactions between simulators and their environments. Algorithms, protocols, and software tools for carrying out quantum simulations will also be put into practice on diverse hardware platforms, laying the groundwork for scalable quantum simulations for science and technology.[59]

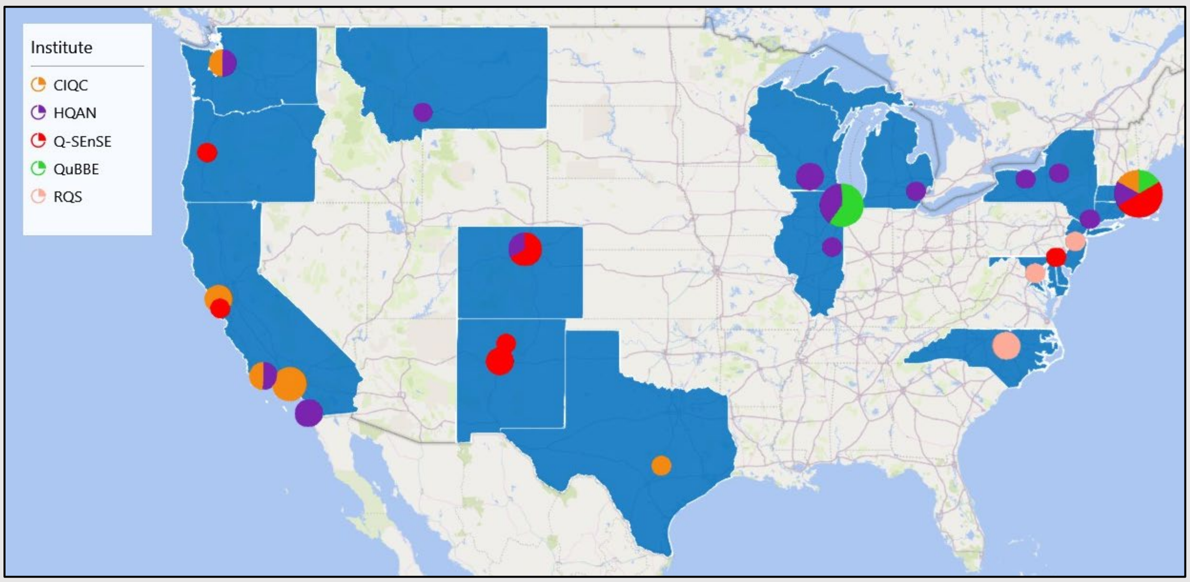

Figure 3.4: Map of the 17 universities, 10 companies, 5 National Laboratories, and 1 Federal R&D agency that are affiliated as partners of QLCI institutes.

[58] https://qubbe.uchicago.edu/
[59] https://rqs.umd.edu/

Box 3.5

Quantum Computing Highlight

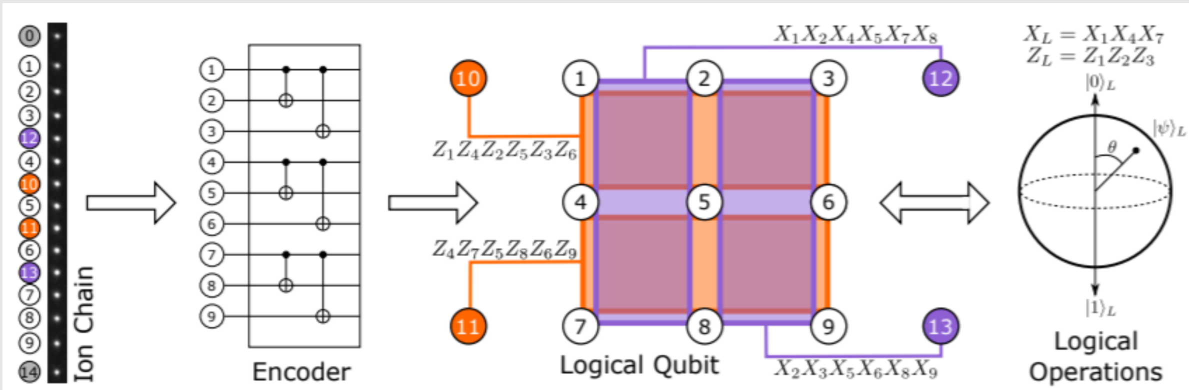

Figure 3.5: A logical qubit built with 13 physical qubits (nine data qubits and four ancilla qubits) used quantum error correction codes to demonstrate improved performance for quantum logic operations.

Quantum error correction, arguably the most important concept for scalable quantum computing, is fundamentally different from classical error correction because qubits cannot be copied. Creating logical qubits using ancillae to stabilize the performance of a set of physical qubits represents a milestone on the long path to making scalable fault tolerant quantum computers.

Researchers at the Joint Quantum Institute, the University of Maryland, Duke University, Ion-Q, and the Georgia Institute of Technology developed a logical qubit using trapped ions, and explored how ancillary qubits (ions 10-13 in Figure 3.5) serve to monitor error syndromes for the logical qubit (made from ions 1-9 in the Figure), using the Bacon-Shor quantum error correction code.[60] Furthermore, they demonstrated fault-tolerant quantum logic operations (preparation, rotations, measurement) on the resulting (single) logical qubit. The result is an experimental proof of principle demonstrating the primitives of quantum error correction, a step toward making quantum logic components that are better than the sum their parts.[61] Next steps include connecting two or more logical qubits, and demonstrating multiple rounds of error correction to stabilize the logical qubit for longer durations.

This work was supported by ARO through the IARPA LogiQ program, the NSF STAQ Program, the AFOSR MURIs on Dissipation Engineering in Open Quantum Systems and Quantum Interactive Protocols for Quantum Computation, and the ARO MURI on Modular Quantum Circuits. It leveraged support from NSF core programs, and it was conducted at the Joint Quantum Institute, a partnership between the University of Maryland and NIST. Support for different parts of this project from multiple U.S. Government agencies is valuable for accelerating discovery and technological spin-offs.

[60] Fault-tolerant control of an error-corrected qubit. *Nature*, 2021; DOI: 10.1038/s41586-021-03928-y; https://arxiv.org/pdf/2009.11482.pdf
[61] https://www.osa-opn.org/home/newsroom/2021/october/a_step_toward_fault-tolerant_quantum_computing/

3.3 The Department of Energy (DOE)

DOE ensures America's prosperity and security through mechanisms including basic and applied scientific research, discovery and development of new technologies, and scientific innovation. The DOE National Laboratories are a system of outstanding intellectual assets, unique among world scientific institutions, that also serve as regional engines of economic growth for States and communities across the country.[62] As authorized by the NQI Act, DOE established five National QIS Research Centers in 2020 (see Box 3.6), and DOE is continuing to strengthen and coordinate QIS research throughout its core programs.

The DOE Office of Science (SC) QIS website https://science.osti.gov/Initiatives/QIS provides public access to SC-sponsored QIS workshop reports and to detailed information about SC QIS programs.[63] Outreach activities funded by the SC and conducted by DOE's National Laboratories are also advertised and have received a strong positive response from the community.[64]

QIS activities span the technical breadth of DOE Office of Science. With investments from all of its research programs - Advanced Scientific Computing Research, Basic Energy Sciences, Biological and Environmental Research, Fusion Energy Sciences, High Energy Physics, the Isotope Program, and Nuclear Physics - DOE's Office of Science supports a diverse portfolio of QIS research on quantum sensing, computing and networking, as well as infrastructure and supporting technology. This is in addition to ongoing QIS research conducted by the DOE National Nuclear Security Administration.

Discussion of how QIS connects to the mission of each DOE component can be found in the SC Program Offices QIS web pages,[65] last year's Annual Report on the NQI Program,[66] and DOE FY 2022 Budget request.[67] In brief:

- Quantum sensing efforts in the core SC research programs include biosensors and bioimaging applications, creation of next-generation detectors and characterization tools, enhancing diagnostic capabilities for plasma and fusion science, using QIS-enabled sensors and experiments to explore new physics and the dark universe, and use of sensors, radiation-resilient quantum circuits and nuclear clocks for nuclear science.
- Quantum computing topics span basic research in algorithms, computer science, software, hardware, quantum simulators, and quantum computing applications in several domains relevant for DOE.
- Quantum networking research and quantum communication projects focus on entanglement distribution, quantum state teleportation, networking of quantum sensors, and the development of quantum networking components, applications, and testbeds.
- Supporting technology for QIS includes infrastructure development in DOE user facilities such as Nanoscale Science Research Centers, and the development and stewardship of technologies for producing isotopes needed for quantum systems.

[62] https://science.osti.gov/Laboratories
[63] https://science.osti.gov/Initiatives/QIS
[64] https://www.quantum.gov/action/large-qis-efforts/#National-Laboratory-QIS-Pages
[65] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages
[66] https://www.quantum.gov/wp-content/uploads/2021/01/NQI-Annual-Report-FY2021.pdf
[67] https://www.energy.gov/sites/default/files/2021-06/doe-fy2022-budget-in-brief-v4.pdf

With a well-established merit-review-based access policy, DOE user facilities continue to support QIS research by offering a suite of advanced resources.[68] Additionally, ORNL's Quantum Computing User Program provides access to industry quantum computing resources to a broad user base,[69] while DOE SC's Quantum Computing Testbeds for Science program provides the research community with fully transparent access to novel quantum computing hardware. The program supports two testbeds: a trapped-ion testbed at Sandia National Laboratory and a superconducting platform at LBNL.[70,71]

DOE launched the National QIS Research Centers in 2020 with a diverse portfolio of research topics (see Box 3.6). The Centers leverage other investments in DOE research and facilities; create synergies with efforts developed by other federal agencies (e. g. NSF Quantum Leap Challenge Institutes and QED-C), the private sector, and academia; and bring unique approaches to community building.

In FY 2021, the DOE SC initiated a program to advance strategic research priorities through the design, development, and demonstration of a quantum internet testbed. For more information about this see the DOE Quantum Internet Blueprint workshop report[72] and funding announcements summarized below.

DOE QIS R&D activity highlights in the news:

Funding announcements: the DOE SC has issued 18 calls for proposals since 2019 that address critical QIS challenges. Recent highlights include:

- (March 9, 2021) DOE Nanoscale Science Research Centers Support QIS Research to Advance Energy, Economic, and National Security.[73]
- (April 13, 2021) DOE to provide $25 Million toward Development of a Quantum Internet.[74] See for example the "Entanglement management and control in transparent optical QN" funding opportunity announcement,[75] and the related DOE Labs opportunity for quantum networking.[76]
- (April 30, 2021) DOE announces $11 Million for Research on QIS for Fusion Energy Sciences.[77]
- (May 6, 2021) DOE announces $10 Million for Research on QIS and Nuclear Physics.[78]
- (July 23, 2021) DOE announces $73 Million for Materials and Chemical Sciences Research to Advance Quantum Science and Technology.[79]
- In FY 2020, DOE's High Energy Physics program renewed the projects funded under its Quantum Information Science Enabled Discovery (QuantISED) program.[80]

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68 https://science.osti.gov/User-Facilities
69 https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/
70 https://qscout.sandia.gov
71 https://aqt.lbl.gov
72 https://www.osti.gov/biblio/1638794/
73 https://www.energy.gov/articles/doe-announces-30-million-quantum-information-science-tackle-emerging-21st-century
74 https://www.energy.gov/science/articles/department-energy-provide-25-million-toward-development-quantum-internet
75 https://science.osti.gov/-/media/grants/pdf/foas/2021/SC_FOA_0002476.pdf
76 https://science.osti.gov/-/media/grants/pdf/lab-announcements/2021/LAB_21-2495.pdf
77 https://www.quantum.gov/doe-announces-11-million-for-research-on-qis-for-fusion-energy-sciences/
78 https://www.quantum.gov/doe-announces-10-million-for-research-on-qis-and-nuclear-physics/
79 https://www.energy.gov/articles/doe-announces-73-million-materials-and-chemical-sciences-research-advance-quantum-science
80 https://science.osti.gov/-/media/hep/pdf/Awards/QuantISED_2020_Renewals_ABSTRACTS.PDF?la=en&hash=4F9F67FABB236BFA1CD051FADE8468B8FD3F00F2

Community Resources: DOE's QIS strategy and programs build on community engagement. The DOE SC has sponsored and organized over 14 QIS roundtable discussions and workshops,[81] along with dozens of community activities organized by DOE National Labs. Some recent workshops include:

- The National Academies of Science, Engineering, and Medicine hosted a DOE workshop on Quantum Sensing and Imaging for Biology in 2021;[82]
- The QED-C and DOE organized a workshop for quantum networking businesses in 2021; and
- DOE Quantum Internet Blueprint workshop, cited earlier.

Box 3.6

National QIS Research Centers: DOE launched five QIS Research Centers in 2020. These are led by National Labs and combine expertise and resources from 69 academic, industry and lab partners from 23 states, the District of Columbia, and Canada and Italy to address a diverse portfolio.[83, 84] The National QIS Research Centers fully leverage the DOE facilities across the lab complex, incorporate industry facilities, use international facilities and build new capabilities such as quantum foundries. The Centers Executive Council is working on identifying a coordinated approach across the portfolio to facilitate access to particular capabilities.

Q-NEXT · Next Generation Quantum Science and Engineering: Q-NEXT will deliver quantum interconnects, establish national foundries, and demonstrate communication links, sensor networks, and simulation testbeds. In addition to enabling scientific innovation, Q-NEXT will build a quantum-smart workforce, create quantum standards by building a National Quantum Devices Database, and provide pathways to the practical commercialization of quantum technology by embedding industry in all aspects of its operations and incentivizing start-ups.[85]

C2QA · Co-design Center for Quantum Advantage: C2QA aims to overcome the limitations of today's noisy intermediate scale quantum (NISQ) computer systems to achieve quantum advantage for scientific computations in high-energy, nuclear, chemical and condensed matter physics. The integrated five-year goal of C2QA is to deliver a factor of 10 improvement in quantum software optimization; a similar improvement in underlying materials and device properties; and comparable improvements in quantum error correction. Then C2QA aims to combine these advances to provide a factor of 1,000 improvement in appropriate computation metrics.[86]

SQMS · Superconducting Quantum Materials and Systems Center: The primary mission of SQMS is to achieve transformational advances in the major crosscutting challenge of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing. In addition to the scientific advances, SQMS will target tangible deliverables in the form of unique

[81] https://science.osti.gov/Initiatives/QIS/Community-Resources
[82] https://www.nationalacademies.org\our-work\quantum-science-concepts-in-enhancing-sensing-and-imaging-technologies-applications-for-biology-a-workshop
[83] https://science.osti.gov/-/media/QIS/pdf/QuantumBrochure2021.pdf
[84] https://science.osti.gov/Initiatives/QIS/QIS-Centers
[85] https://www.q-next.org/
[86] https://www.bnl.gov/quantumcenter/

foundry capabilities and quantum testbeds for materials, physics, algorithms, and simulations that could broadly serve the national QIS ecosystem.[87]

QSA · Quantum Systems Accelerator: QSA aims to co-design algorithms, devices, and engineering solutions to deliver certified quantum advantages in scientific applications. QSA's multidisciplinary team will pair advanced quantum prototypes based on neutral atoms, trapped ions, and superconducting circuits with algorithms specifically constructed for imperfect hardware, to demonstrate optimal applications for each platform in scientific computing, materials science, and fundamental physics. The QSA will deliver prototypes to explore the quantum technology trade-space, laying the scientific foundation to accelerate the maturation of commercial technologies.[88]

QSC · Quantum Science Center: QSC aims to overcome roadblocks for quantum state resilience, controllability and scalability, ultimately in support of quantum technologies. This goal will be achieved through integration of the discovery, design, and demonstration of topological quantum materials, algorithms, and sensors, catalyzing the development of disruptive technologies. In addition to the scientific goals, QSC activities will develop the next generation of QIS workforce by creating a rich environment for professional development and close coordination with industry to transition new QIS applications to the private sector.[89]

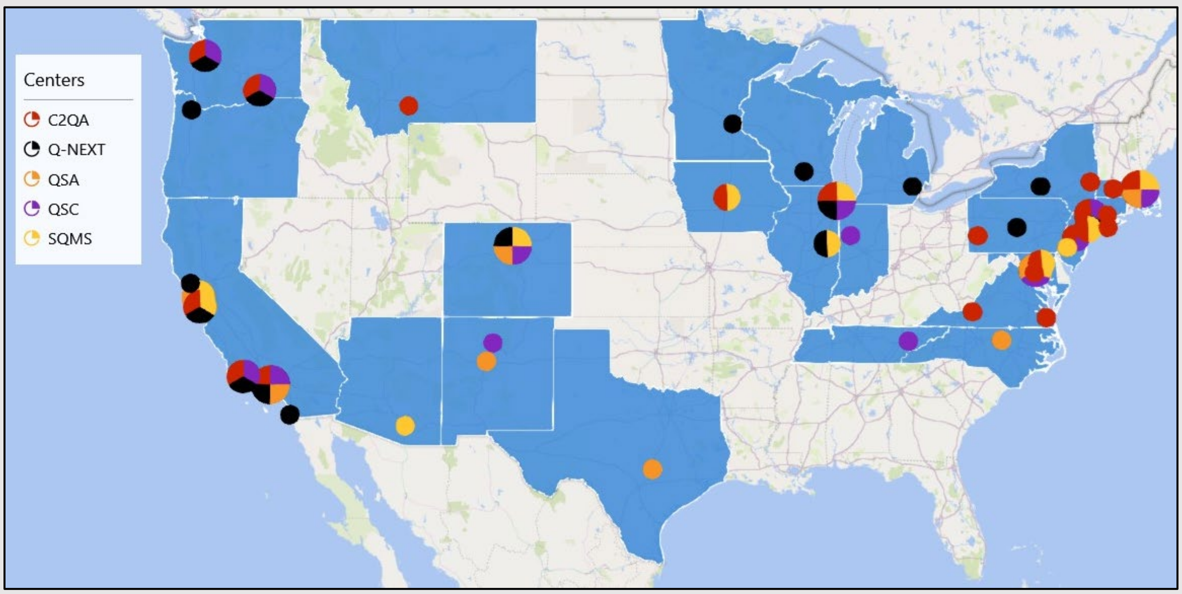

Figure 3.6: Map of the 38 universities, 15 companies, 12 National laboratories and 2 federal R&D agency labs that are part of the DOE National QIS Research Centers

[87] https://sqms.fnal.gov/
[88] https://quantumsystemsaccelerator.org/
[89] https://qscience.org/scientific-thrusts/

Box 3.7

Highlight: Cosmic Rays and Qubits

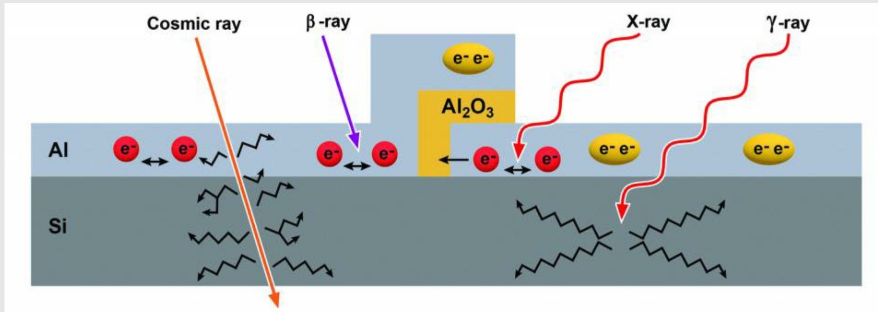

Figure 3.7: Naturally occurring cosmic rays can limit the performance of quantum computers. An impinging particle ionizes the superconducting substrate, radiating high energy phonons that induce a burst of quasiparticles, destroying qubit coherence. Image Courtesy of Michael Perkins, PNNL.

One of the biggest challenges to creating a fully capable quantum computer is to build qubits that can store information long enough to perform an efficient error-corrected calculation. This quality of a qubit is called coherence. Many forces can destroy, or decohere, the delicate prepared state of a qubit. Researchers at Pacific Northwest National Laboratory (PNNL) and the Massachusetts Institute of Technology (MIT) demonstrated the connection between radiation, the excess of unpaired electrons, and their harmful effects on superconducting qubits. Specifically, the coherence times were reduced under elevated radiation from a radioactive source. Coherence times increased when devices were shielded from natural radiation. While other effects are primarily responsible for the current limits of around 100 microseconds, environmental radiation could eventually limit coherence to a few milliseconds without adequate mitigation strategies in the years ahead as qubit materials and manufacturing improve.[90,91,92]

This discovery has already stimulated research on radiation-hardening of quantum computers and quantum sensors, for example, with quasiparticle traps or electrodes to channel away unwanted excitations or in-situ sensor-assisted quantum fault mitigation. The implications for quantum error correction, in the case of radiation-induced quasiparticle bursts, is a new line of research stimulated by this finding as well.

This work is supported by the DOE Nuclear Physics program, and it leveraged collaborative QISE R&D efforts sponsored by the Air Force, ARO, NSF, PNNL, and MIT Lincoln Laboratories, a Federally Funded Research and Development Center. Collectively, these QIS programs and others highlighted throughout this report accelerate basic research on qubits and quantum technology.

[90] https://www.pnnl.gov/publications/impact-ionizing-radiation-superconducting-qubit-coherence
[91] https://www.pnnl.gov/news-media/natural-radiation-can-interfere-quantum-computers
[92] Vepsäläinen, A.P., Karamlou, A.H., Orrell, J.L. et al. Impact of ionizing radiation on superconducting qubit coherence. Nature 584, 551–556 (2020). https://doi.org/10.1038/s41586-020-2619-8

3.4 The Department of Defense (DOD)

The DOD Research & Engineering mission supports the national defense strategy via basic and applied research, advanced technology development, and through operational test and evaluation of new technologies. Quantum science is one of DOD's top 11 modernization priority areas, and has been a focus of sustained DOD funding for almost thirty years. DOD continues substantial investments in basic QIS R&D activities via several offices, agencies and laboratories including: the Office of the Under Secretary of Defense for Research and Engineering [OUSD(R&E)]; the Defense Advanced Research Projects Agency (DARPA); the Army Research Laboratory (ARL), the Army Research Office (ARO); the Naval Research Laboratory (NRL); the Office of Naval Research (ONR), the Air Force Research Laboratory (AFRL); and the Air Force Office of Scientific Research (AFOSR). The National Defense Authorization Act legislated enhancements to the Defense Quantum Information Science and Technology Research and Development Program such as the establishment QIS Research Centers (see Box 3.8).

DOD QIS R&D activity highlights:

- The Office of the Under Secretary of Defense for Research and Engineering appointed a Principal Director for Quantum Science in 2018 to lead DOD technology modernization efforts in QIST.
- Single investigator programs and Young Investigator Programs (YIP) run by ARO, ONR, and AFOSR in fields such as materials science, condensed matter, atomic, and optical physics provide a scientific backbone that underpins many QIS efforts. Accomplishments from these programs provide a foundation for developing quantum technologies.
- DOD quantum R&D programs span atomic clocks, quantum sensing, quantum computing, and quantum networking, from fundamental to applied R&D.
- The Center for Excellence in Advanced Quantum Sensing supported by OUSD(R&E) and managed by ARL, is at Delaware State University,[93] an Historically Black College and University and Minority Serving Institution. Increasing diversity and inclusion in QIST research is a priority for the DOD and the NQI.
- ARL co-founded the Quantum Technology Center[94] (QTC) with University of Maryland in 2019. NRL joined the QTC in September of 2020 as an additional partner.[95]
- <u>Atomic clocks:</u> R&D programs that support long-term efforts on precision timekeeping include: ONR's Next Generation Atomic Clock (NGAC)[96] program, ARL's Low-Cost Chip-Scale Atomic Clock (LC CSAC)[97] program, the U.S. Naval Observatory (USNO) timekeeping research for the USNO Master Clock, and AFRL's Quantum Sensing and Timing Program. Atomic clocks developed with these programs could support DOD missions by enabling synchronization of secure communication networks and enhanced, more resilient, navigation capabilities with devices that have lower cost, size, weight, and power (C-SWaP).
- <u>Quantum Sensors:</u> R&D programs to develop gyroscopes, accelerometers, magnetometers, gravimeters, and electrometers include the OUSD(R&E)/ARL Center for Excellence in Advanced

[93] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/
[94] https://www.qtc.umd.edu
[95] https://www.nrl.navy.mil/Media/News/Article/2368835/nrl-maryland-virtually-sign-partnership-on-quantum-technologies/
[96] https://www.onr.navy.mil/-/media/Files/Funding-Announcements/Special-Notice/2020/N00014-20-S-SN17.ashx
[97] https://www.arl.army.mil/lccsac/

Quantum Sensing,[98] DARPA's Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT),[99] Atomic-Photonic Integration (A-PhI),[100] and Science of Atomic Vapors for New Technologies (SAVaNT)[101] programs, the Army's metrology program, ARL's electromagnetic field sensing with Rydberg atoms,[102] ARO's MURI on quantum state engineering for enhanced metrology,[103] ONR's work on atom interferometer inertial and gravity sensors, the AFRL strategic atomic navigation devices and systems (SANDS),[104] and the AFOSR MURI on cold molecules.[103]

- Quantum Computers: The DoD Basic Research Office and its Military Service counterparts, the ARO, ONR, and AFOSR, have led foundational research in quantum computing for over three decades with both in-house and external funding programs such as the Single Investigator programs, the Vannevar Bush Faculty Fellowship program and the Multidisciplinary University Research Initiative (MURI) program topics. Ongoing basic research efforts include DARPA's Optimization with Noisy Intermediate Scale Quantum devices (ONISQ) program[105] and its Quantifying Utility of Quantum Computers (Quantum Benchmarking)[106] program, the AFOSR MURI on quantum programming languages, the ARO/AFOSR MURI on modular quantum computing, an AFOSR MURI on Dissipation Engineering and an AFOSR MURI on quantum random access memory.
- Quantum Networks: ARL's Center for Distributed Quantum Information (CDQI) was a collaborative basic research effort to develop a multi-site, multi-node, modular quantum network based on resilient distributed quantum entanglement preserved by quantum memory and quantum error correction. Current quantum network efforts include an ARO MURI on quantum network science, an AFOSR MURI on quantum optics (Quantum Many-Body Physics with Photons), and an AFOSR MURI on Quantum Information Concepts from Tensor Networks.

DOD QIS R&D activities highlighted in the news:

- ONR/ARO/AFOSR Broad Agency Announcement (BAA) topics include: Quantum Network Science, Quantum Sensing, Quantum Computing, and Quantum Random Access Memory. [107, 108]
- (September 1, 2020) the DARPA Science of Atomic Vapors for New Technologies (SAVaNT) program seeks to advance the performance of room-temperature atomic vapors to enable future opportunities for low size, weight, and power (SWaP).[109]
- (January 15, 2021) The Air Force and Space Force established a new partnership between the AFRL and NSF to advance the scientific and innovation skills of the United States and draw a whole new generation of globally-competitive, diverse scientists and engineers into the AFRL innovation ecosystem. The partnership, which is part of the NSF INTERN program, formalizes an opportunity

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98 https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/
99 https://www.darpa.mil/program/atomic-magnetometer-for-biological-imaging-in-earths-native-terrain
100 https://www.darpa.mil/program/atomic-photonic-integration
101 https://www.darpa.mil/program/science-of-atomic-vapors-for-new-technologies
102 https://www.army.mil/article/242980/army_researchers_detect_broadest_frequencies_ever_with_novel_quantum_receiver
103 https://www.cto.mil/wp-content/uploads/2020/02/fy2020-muri-press-release.pdf
104 https://afresearchlab.com/technology/quantum/
105 https://www.darpa.mil/news-events/2020-05-11a
106 https://www.darpa.mil/news-events/2021-04-02
107 https://www.onr.navy.mil/-/media/Files/Funding-Announcements/Special-Notice/2020/N00014-20-S-SN17.ashx
108 https://www.arl.army.mil/wp-content/uploads/2020/04/ARO-BAA-Amendment-7-Final.pdf
109 https://www.darpa.mil/news-events/2020-09-01a

for current and future NSF-funded graduate students to participate in six-month internships onsite at any of eight AFRL technology directorates.[110]

Box 3.8

DOD QIST Centers: DOD established two QIST Centers, pursuant to the FY 2020 National Defense Authorization Act (NDAA) Section 220. These Centers provide additional authorities and opportunities for DOD sites to accelerate QIST R&D.

- **NRL** was designated as the Navy's Quantum Information Research Center[111] in March 2020, by the Deputy Assistant Secretary of the Navy for Research Development Test and Evaluation (RDT&E) to enhance and accelerate the research, development, and deployment of quantum information sciences and quantum information science-enabled technologies and systems.[112]
- **AFRL** was designated as the QIS Research Center for the U.S. Air Force and U.S. Space Force in April 2021.[113] This designation grants additional authorities to the AFRL Information Directorate as part of the DOD QIST program under the NDAA. It will also leverage the Quantum Center of Excellence that AFRL established with its Innovare campus in Rome, New York, in partnership with the State University of New York (SUNY) and several other entities.[114]

- (January 29, 2021) AFRL researchers measured superconducting qubit coherence times, marking progress towards qubit characterization capabilities in DOD service labs.[115]
- (April 5, 2021) DARPA announced the Quantum Benchmarking - Quantifying Utility of Quantum Computers program,[116] which is designed to provide standards to measure quantum computing progress against and drive current research toward specific goals. Meaningful metrics will help quantify the potential utility of transformative large-scale quantum computers.
- (April 8, 2021) DARPA launched the Quantum Apertures (QA) program to develop fundamentally new ways of receiving radio frequency (RF) waveforms to improve both sensitivity and frequency agility for defense applications. The QA program aims to develop RF antennas, or apertures, that use quantum techniques to alter the way the RF spectrum is accessed. The goal is to develop portable and directional RF receivers with significantly greater sensitivity, bandwidth, and dynamic range than any classical receiver available today.[117]
- (April 9, 2021) DOD released a funding announcement for FY 2022 MURIs including a topic on Synthetic Quantum Matter.[118]
- (April 21, 2021) The ARO and LPS released a BAA for its Next New and Emerging Qubit Science & Technology program,[119] which is focused on qubit systems that explore new operating regimes and environments, as well as new methods of fabrication, design, control, or operation.
- (April 27, 2021) DOD launched the Center of Excellence in Advanced Quantum Sensing (COE-AQS).[120] This is an HBCU/MSI center managed by ARL, focusing on entanglement-enhanced quantum sensing, e.g., spin-squeezing in atomic clocks and magnetometers.

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110 https://www.afrl.af.mil/News/Article/2473878/new-afrl-collaboration-with-nsf-intern-program-opens-aperture-for-recruiting-to/
111 https://www.nrl.navy.mil/Media/News/Article/2368962/nrl-designated-navys-quantum-information-research-center/
112 https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Quantum-Research/
113 https://www.afrl.af.mil/News/Article-Display/Article/2724770/air-force-research-laboratory-designated-as-quantum-information-science-researc/
114 https://www.innovare.org/
115 https://www.quantum.gov/afrl-measures-first-superconducting-quantum-bits-qubit-first-ever-demo-for-a-dod-service-lab/
116 https://www.quantum.gov/darpa-announces-new-program-to-quantify-utility-of-quantum-computers/
117 https://www.darpa.mil/news-events/2021-08-04
118 https://www.quantum.gov/dod-releases-funding-announcement-for-fy2022-muris-several-focused-around-qis/
119 https://www.quantum.gov/aro-and-lps-release-baa-for-nextneqst/
120 https://www.quantum.gov/defense-department-launches-center-of-excellence-in-advanced-quantum-sensing/

- (February 24, 2021) The ARL/ARO Center for Distributed Quantum Information (CDQI) Program supported work to deterministically transmit multi-qubit entangled states on a quantum network, highlighted in Box 3.9.

Box 3.9

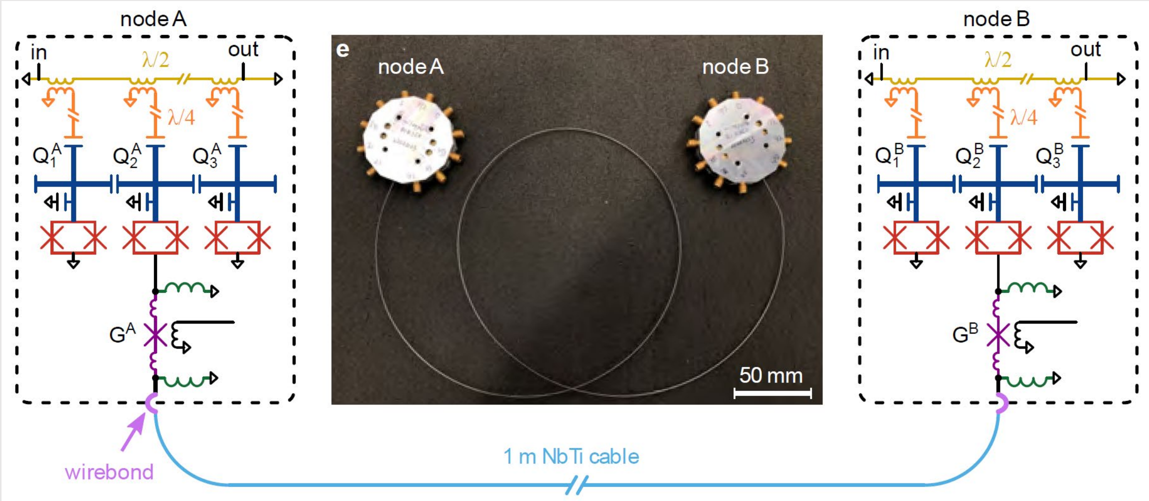

Figure 3.9: Quantum networking experimental hardware and circuit schematic diagram; courtesy of A. Cleland.

Quantum Networking Highlight: A joint research team from the University of Chicago and Argonne National Laboratory reported the first deterministic transmission of multi-qubit entangled states using a quantum network.[121] The team used a one meter long superconducting coaxial cable seen in Figure 3.9 to connect a pair of three-qubit quantum nodes, thus laying groundwork for modular quantum computing and quantum networking.

While previous experiments entangled two remote qubits, the deterministic generation and transmission of multi-qubit entanglement has remained elusive. This team used superconducting wire bonds directly between the cable and the qubits to minimize losses, and developed a hybrid quantum state transfer scheme to balance losses in the cable and in the qubits. Together, these innovations enabled two key results for distributing quantum information: the successful deterministic generation and transmission of an entangled three-qubit state from one node to another, and the successful expansion of two-qubit remote entanglement into a greater-than-two qubit, multi-node entangled state. Both experiments achieved state fidelities above the threshold for genuine multipartite entanglement, demonstrating the promise of this approach for future quantum computers and networks.

Decades of sustained support in fundamental QIS R&D by multiple Federal agencies enabled this team to achieve these results. Additionally, direct support from the DOD, DOE, NSF, LPS, and private foundations in line with their respective agency goals enabled different facets of this experiment to succeed, demonstrating the crucial nature of interagency coordination in distributed entanglement research. Major challenges in this field lie ahead both related to the larger scale experimental realization of multi-qubit distributed entanglement and the further elucidation and evaluation of use cases for distributed entanglement and quantum networks for government and civilian benefit.

[121] https://www.army.mil/article/244139/army_funded_research_lays_groundwork_for_future_quantum_networks; https://www.nature.com/articles/s41586-021-03288-7

3.5 The National Aeronautics and Space Administration (NASA)

NASA drives advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth. NASA's quantum research portfolio includes several activities led by the Quantum Sciences and Technology Group at NASA Headquarters, and its Glenn Research Center, Ames Research Center, and Goddard Space Flight Center, along with other NASA laboratories and federally funded research centers (FFRDCs).

NASA QIS R&D activity highlights

- NASA's Quantum Artificial Intelligence Lab (QuAIL) at NASA Ames serves as the space agency's hub for assessing the potential of quantum computers to impact computational challenges faced by the agency. Since 2012, QuAIL has published over 75 peer reviewed QIS papers.[122] QuAIL is also a member of two of the DOE National Quantum Research centers, C2QA and SQMS.
- NASA has begun exploring the design, development, and deployment of high-rate and high-fidelity space-to-ground quantum network links. To this end, NASA, NRO and NIST collaborated on a Workshop on Space Quantum Communications and Networks.[123]
- NASA has several Space Act agreements in place to engage with the private sector on assessment and utilization of quantum processors.
- A DOE and NASA Request for Information (RFI) from February 2021 included a query about possible experiments on the ISS that make use of quantum sensor technologies and capabilities for the high energy physics, astrophysics, and biological and physical sciences.[124]
- NASA has carried out a series of studies on advanced annealing schedules that provided orders of magnitude improvement over standard annealing schedules.[125]
- An agreement between NASA and the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) seeks further understanding of Quantum technologies and potential applications.
- The Fundamental Physics program of NASA's Biological and Physical Sciences (BPS) Division has held workshops to discuss space-based quantum optics for fundamental physics, and prospects for NASA's Deep Space Quantum Link (DSQL) mission concept.[126]
- The Cold Atom Laboratory (CAL) on the International Space Station will make use of the space station's unique microgravity environment to observe quantum phenomena that would otherwise be undetectable from Earth.[127]
- NASA's Glenn Research Center, Ames Research Center, and Goddard Space Flight Center are organizing a conference on QIS advances and potential applications.[128]

[122] https://ti.arc.nasa.gov/tech/dash/groups/quail/
[123] https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings
[124] https://www.quantum.gov/rfi-on-space-based-astrophysics-includes-quantum-sensors/
[125] Phys. Rev. Research 2, 023020 (2020), arXiv:2006.08526 (2020)
[126] https://techport.nasa.gov/view/94990
[127] https://coldatomlab.jpl.nasa.gov/
[128] https://events.grc.nasa.gov/quantum/

3.6 The National Security Agency (NSA)

NSA's Laboratory for Physical Sciences (LPS) sponsors research on quantum computing and enabling technologies, as it has since the 1990s. LPS funds extramural research around the country and the world. LPS also supports a robust internal research program at its University of Maryland, College Park facility. LPS funds a broad array of quantum information science and technology research both directly and in partnership with ARO.[129] In 2021, LPS launched the first-ever *Qubit Collaboratory* (see Box 3.10) and released a public request for information (RFI) for a Qubits for Computing Foundry.

LPS QIS R&D activity highlights:

- LPS quantum computing research programs include: the High Performance Superconducting Qubit Systems (HiPS) program; the Qubits in Silicon (QiS) program; the Stable High Fidelity Trapped Ion Systems (SHiFT) program; the Quantum Characterization of Intermediate-Scale Systems (QCISS) program;[130] the New & Emerging Qubit Science & Technology (NEQST) program;[131] and the Cross-Quantum Technology Systems (CQTS) program.[132]
- LPS funds graduate student and postdoctoral fellowships via the Quantum Computing Research (QuACR) fellowship program, direct partnerships with universities such as the University of Maryland and MIT, and through its sponsored and internal research programs.
- LPS is a founding supporter of MIT's Center for Quantum Engineering and a founding member of the Joint Quantum Institute and the Joint Center for Quantum Information and Computer Science at the University of Maryland.
- LPS co-chairs the NSTC ESIX Subcommittee to promote the understanding of the national security implications of quantum science and co-chairs the SCQIS Workforce Working Group.

Box 3.10

Qubit Collaboratory The LPS Qubit Collaboratory (LQC)[133], a National QIS Research Center supporting the National Quantum Initiative, was established to engage industry, national labs, and academia through collaborative partnerships to pursue disruptive research on qubit technologies for computing and sensing. The LQC also seeks to build a quantum workforce through research experiences and innovative training in government at LPS and at LQC partners.

- The LQC supports incubator research proposals and sabbaticals, multi-year and cross-institutional research proposals, and QuACR fellowships across the nation.
- Qubit foundry seedling efforts were initiated in 2021 to enable community access to state-of-the-art qubit devices to accelerate exploration of qubit physics.

3.7 The Intelligence Advanced Research Projects Activity (IARPA)

IARPA sponsors high-risk, high-payoff R&D to deliver innovative technologies to the intelligence community and the Federal government. Over the last decade, this involved several research programs on quantum computing. Recent and ongoing activities include Quantum Enhanced Optimization (QEO) on quantum annealing, and the LogiQ program for development of logical qubits.[134]

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[129] http://www.lps.umd.edu/solid-state-quantum-physics/index.html
[130] https://beta.sam.gov/opp/4e2a92e50c67472785de05973051463a/view?index=opp&page=4
[131] https://www.quantum.gov/aro-and-lps-release-baa-for-nextneqst/
[132] https://www.qubitcollaboratory.org/about/lps-solid-state-and-quantum-physics-programs/
[133] https://www.quantum.gov/nsas-laboratory-for-physical-sciences-announces-first-ever-qubit-collaboratory/
[134] https://www.iarpa.gov/index.php/research-programs/quantum-programs-at-iarpa

Box 3.11

Quantum Simulation Highlight

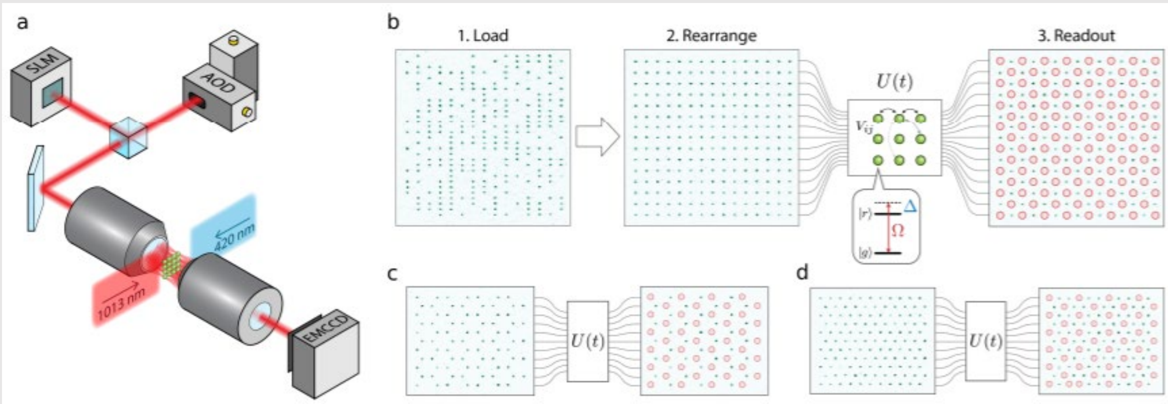

Figure 3.11: A programmable quantum simulator based on arrays of neutral atoms with tunable interactions was used demonstrate new quantum phases and quantitatively probe the associated phase transitions.

Programmable quantum simulators use well controlled assemblies of physical objects to investigate complex behaviors of complex systems. Complimentary to digital quantum computers, quantum simulators can directly emulate other systems that may be inaccessible in the laboratory. They can also explore complex many-body phenomena that are difficult to compute.

As an example of quantum simulation, researchers at Harvard, MIT, the University of Innsbruck, and QuEra Computing collaborated to investigate quantum phase diagrams using two-dimensional arrays of trapped neutral atoms with tunable interactions. They observed novel quantum phases that exhibit long-range order as shown in Figure 3.11.[135] Their study of phases, defects, and dynamics of quantum phase transitions shed light on universal behaviors of quantum many-body systems, and illustrate how programmable quantum simulators can be used to study large systems that are challenging to model with standard computational methods.

Parts of this research were supported by the NSF Physics Frontiers Center program, the Vannevar Bush Faculty Fellowship program, the DOE National QIS Research Center program, ONR, an ARO MURI, and the DARPA ONISQ program. Support for different aspects of this project from multiple U.S. Government agencies is valuable for promoting collaborations and accelerating discovery, training, and technological spin-offs.

Future applications of programmable quantum simulators may include exploration of entanglement dynamics, topological quantum states, lattice gauge theories, and spin models relevant for chemistry and materials science. Computational tasks such as optimization and sampling may also be potentially accelerated using quantum simulators. The possibility of hardware-efficient multi-qubit operations and novel protocols for fault-tolerant control motivate further work.

Selected QIS R&D highlights presented in Boxes and points throughout this Section show only a representative sampling of the recent breakthroughs and capabilities that have been accelerated by National Quantum Initiative activities.

[135] Quantum phases of matter on a 256-atom programmable quantum simulator. Nature, 595(7866), p. 227, https://doi.org/10.1038/s41586-021-03582-4; https://arxiv.org/pdf/2012.12281.pdf

4 QIS Policy Areas

The *National Strategic Overview for QIS* provides recommendations to strengthen the U.S. approach to QIS R&D, focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation, as shown in Figure 4.1. The following sections of this report (4.1 – 4.6) present a brief overview of policy goals for each of these topics, along with highlighted activities undertaken across the Federal government to fulfill these objectives.

Figure 4.1: Policy topics discussed in the National Strategic Overview for QIS.

4.1 Choosing a Science-First Approach to QIS

Investment in fundamental science provides a foundation for the Nation's prosperity and security.[136] Historically, the exploration of quantum mechanics precipitated transformative technologies such as atomic clocks and the global positioning system, lasers, transistors, and magnetic resonance imaging. Meanwhile, the exploration of information theory precipitated transformative advances in communication, computation, and data science. The confluence of these fields creates new scientific vistas to explore, with compelling potential for new QISE applications and use cases. One of the ongoing challenges is to balance efforts between particular technologies and fundamental science.

Many in the scientific, business, and academic communities have asserted that QIS holds tremendous opportunities for revolutionary technologies,[137] but investments in basic research are needed to establish critical technical foundations. Therefore, it is the policy of the United States to establish and lead the scientific development of QIS. Exploring fundamental problems in QIS and its enabling technologies is prioritized as a means to produce new understanding, develop new capabilities, and

[136] V. Bush, *Science the Endless Frontier* (1945) https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm
[137] See the Quantum Frontiers Report (2020); federally funded QIS workshop reports; the 2019 White House Academic Roundtable on QIS; and the 2018 White House Summit on QIS Summary: https://www.quantum.gov/wp-content/uploads/2021/01/2018_WH_Summit_on_QIS.pdf

nurture a culture of discovery. Implementing this science-first approach entails strengthening core QIS R&D programs, launching new QIS centers, and exploring quantum frontiers. The following actions support this approach:

- The SCQIS coordinates QIS R&D across relevant agencies by sharing information and developing policy recommendations. The SCQIS has routine discussions, convenes events, and forms Interagency Working Groups (IWG) for various topics. The SCQIS, with support from the NQCO, launched the website www.quantum.gov to help coordinate and showcase NQI activities.[138]
- The *Quantum Frontiers Report* elaborates on a science-first approach by listing eight areas where breakthroughs on QIS grand challenges will be transformative for R&D.[139] These include:
    - Expanding Opportunities for Quantum Technology to Benefit Society
    - Building the Discipline of Quantum Engineering
    - Targeting Materials Science for Quantum Technologies
    - Exploring Quantum Mechanics through Quantum Simulations
    - Harnessing QIS Technology for Precision Measurement
    - Generating and Distributing Entanglement for New Applications
    - Characterizing and Mitigating Quantum Errors
    - Understanding the Universe through Quantum Information

  These quantum frontiers are based on a synthesis of community feedback from an RFI and three dozen federally-funded QIS workshops, roundtables, and studies.
- *A Strategic Vision for America's Quantum Networks* was released in coordination with the SCQIS.[140] This policy document led to the development of the Quantum Networking IWG and the further development of a coordinated approach to quantum network R&D.
- With the growing number of efforts on quantum networking research, the Quantum Networking IWG produced *A Coordinated Approach to Quantum Networks Research* to highlight technical and programmatic recommendations (TR and PR) for actions Federal agencies can take to advance the Nation's knowledge base and readiness to utilize quantum networks: [141]
    - TR 1: Continue Research on Use Cases for Quantum Networks
    - TR 2: Prioritize Cross-Beneficial Core Components for Quantum Networks
    - TR 3: Improve Classical Capabilities to Support Quantum Networks
    - TR 4: Leverage "Right-Sized" Quantum Networking Testbeds
    - PR 1: Increase Interagency Coordination on Quantum Networking R&D
    - PR 2: Establish Timetables for Quantum Networking R&D Infrastructure
    - PR 3: Facilitate International Cooperation on Quantum Networking R&D
- The SCQIS Science IWG and NQCO convene an annual QIS Program Day that brings together QIS program managers from across the government to discuss projects and directions for QIS R&D. This year will mark the third annual meeting.
- Centers and institutes recently established by DOE and NSF will bring together thousands of scientists, engineers and technicians to investigate the basic scientific principles underlying QIS. To support this action, the NSF, NIST and DOE held an NQI Community meeting in December of 2020.

[138] https://www.quantum.gov/
[139] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[140] https://www.quantum.gov/wp-content/uploads/2021/01/2020_NQCO_Vision_QN.pdf
[141] https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf

- The SCQIS established a Quantum Sensors Joint IWG that connects the Science IWG with the End-Users IWG. The intent of the group is to identify challenges and potential recommendations to support the transitions of quantum sensors from the lab to the field.
- The Washington Metro Quantum Network Research Consortium (DC-QNet) is in the process of being formally established as a group of leading U.S. Government quantum research organizations in the Washington DC area to provide a multi-agency fiber-based quantum networking test bed. With member organizations consisting of ARL, USNO, NIST, NASA, NSA, and NRL and with associate members AFRL and NIWC-Pacific, DC-QNet leverages the unique technical expertise from each agency to focus on both near- and long-term technical challenges and applications of quantum networking.
- Many of the QIS R&D efforts highlighted in Section 3 also benefit from coordination among several Federal agencies.

4.2 Creating a Quantum-Smart Workforce for Tomorrow

The United States has built a strong foundation for QIS R&D over the past few decades, with a baseline level of research infrastructure and a scientific and technical workforce comprising talented college graduates, Ph.D. students, postdocs, staff scientists, and professors. The workforce has grown through the steady process of funding fundamental research and through job opportunities at universities, Federal laboratories, and quantum-adjacent industry. This approach naturally depends year-by-year on the pace of scientific breakthroughs and the level of support from agencies. This organic, market-driven quantum workforce has seen a tremendous strain as the need for technical talent outstrips supply because of the tremendous increase in domestic QIS industry investment and worldwide efforts in QIS R&D. Additionally, the field is poised for more growth because of the projected applications for QIS technologies. Given the present and anticipated increases in QIS jobs, and the long time-horizon for training, the existing supply of crucial talent is well below the current demand. To support workforce development, the following actions have been undertaken:

- The SCQIS is coordinating workforce development across its member agencies through its IWG on Workforce. The IWG has been engaging with education and industrial communities, the QED-C, and other agencies to understand the supply and demand for a QIS workforce. As a major funder of workforce development, and in recognition of the interdisciplinary nature of QIS, NSF has formed its own working group to ensure coordination across several of its directorates.
- The National Q-12 Education Partnership is a public-private partnership spearheaded by NSF and the NQCO in OSTP to facilitate growth of the quantum community, starting with early education.[142] The Q-12 Education Partnership members are curating resources for QIS education and outreach. They are showcasing examples of careers in QIST.[143] Teacher development opportunities related to QISE were supported by NSF and Q-12 partners over the Summer of 2021.[144,145] An expansion of the QIS Concepts for future learners was also undertaken.[146]

[142] https://www.q12education.org
[143] https://www.quantum.gov/summary-of-the-national-q-12-education-partnership-kick-off-event/
[144] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2015205&HistoricalAwards=false
[145] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2009351
[146] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2039745

- Workforce development is an important result from the support and training of graduate students and post-doctoral researchers. The majority of R&D activities discussed in Section 3 directly involve contributions from students and postdocs.
- NIST continues to support students and postdocs working in the QIS arena through a range of programs, including ongoing activities at their joint institutes (JILA, JQI, and QuICS).
- NSF places a primary focus on the development of a broad-based, diverse workforce for QIS. Activities include QISE-NET,[147] Quantum Science Summer Schools jointly supported by NSF, AFOSR and DOE,[148] NSF Quantum Computing & Information Science Faculty Fellows program,[149] support of their Graduate Research Fellowship Program,[150] the National Q-12 Education Partnership mentioned earlier, and the NSF Research Traineeship (NRT) Program which recently added QISE.[151]
- NSF sponsored a workshop on Quantum Engineering Education.[152] The workshop focused on the education tracks of potential quantum engineers at the undergraduate level.
- NSF released a Dear Colleague Letter "Advancing Quantum Education and Workforce Development" and held a series of webinars to support community interest.[153,154]
- NASA has competed funding opportunities for its early-career scientists and engineers, civil servants and contractors directed research support, and summer and year-round internships in pure and applied areas across the QIS spectrum.
- LPS released a BAA in partnership with ARO to launch an LPS Qubit Collaboratory (LQC) that specifically includes research thrusts to accelerate QIS learning.[155] LPS also supports the Quantum Computing Research (QuaCR) Fellowships for graduate students and postdoctoral researchers.
- DOE's Workforce Development for Teachers and Scientists program has added QIS topics to its Office of Science Graduate Student Research activity. DOE National Labs continue to organize numerous summer schools, internships, and other opportunities to improve training and research engagement. Additionally, the DOE's Computational Science Graduate Fellowship is actively expanding its support of QIS focused students.
- In FY 2020, DOE Nuclear Physics program established the InQubator for Quantum Simulation that supports researchers, visitors, and community-driven workshops at the Institute of Nuclear Theory at the University of Washington, along with close connections to national laboratories and technology companies, to help create and disseminate new ideas and grow a quantum-ready workforce.
- DOD supports training for QIS R&D through several programs including: the Vannevar Bush Faculty Fellowship program (VBFF);[156] the Multidisciplinary University Research Initiatives (MURI) Program;[157] the Laboratory University Collaboration Initiative (LUCI);[158] the Army's Educational

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[147] https://qisenet.uchicago.edu/
[148] http://qs3.mit.edu/
[149] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505535
[150] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=6201
[151] https://www.quantum.gov/the-nsf-research-traineeship-nrt-program-adds-qise/
[152] NSF Workshop on Quantum Engineering Education - National Quantum Initiative
[153] https://www.quantum.gov/advancing-quantum-education-and-workforce-development/
[154] https://www.quantum.gov/nsf-organizes-special-webinar-for-dcl-advancing-quantum-education-and-workforce-development/
[155] https://www.quantum.gov/lps-qc-learning-of-quantum-information-concepts/
[156] https://basicresearch.defense.gov/Programs/Vannevar-Bush-Faculty-Fellowship/
[157] https://www.cto.mil/2021-muri/
[158] https://basicresearch.defense.gov/Pilots/Laboratory-University-Collaboration-Initiative/

Outreach Program;[159] and the National Defense Science and Engineering Graduate Fellows program,[160] among others.
- A report on *The Role of International Talent in Quantum Information Science*[161] was released by the ESIX Subcommittee in 2021.

4.3 Deepening Engagement with Quantum Industry

The Nation's economic growth and prosperity relies on strong established industries and a vibrant ecosystem for innovation. Basic research fuels this ecosystem by creating new scientific understanding, new materials, new processes, new technologies, and training for the technical workforce that keeps the United States at the forefront of industry capabilities. At the same time, the growth of new industries enables new scientific discoveries and empowers more of the Nation to benefit.

However, the successful translation of scientific discoveries to deployed technologies is challenging. It involves careful handoffs between scientists, engineers, developers, venture capitalists, entrepreneurs, manufacturers, and customers, working together in an innovation ecosystem. Therefore, it behooves the United States to search for, and when appropriate, kick-start quantum technologies by careful support of pathways and connections throughout the innovation community. Early stage support to transition emerging technologies out of the lab is often appropriate when a full market has not yet developed, or when the federal government has a need for particular applications or capabilities to be developed, especially if investors are reluctant to take on the full cost and potential risk associated with translating the research. To this end, agencies organized around the NQI have undertaken the following efforts to support and engage with the quantum industry.

- The White House hosted a Summit on Quantum Industry and Society, on October 5th 2021 (see Figure 1). The Summit touched on three themes: anticipated impacts on society due to quantum computing and quantum sensing technologies; pathways to ensure American competitiveness for these emerging technologies; and ways to broaden participation in the QISE ecosystem.[162]
- The SCQIS established an End-User IWG to connect developers with potential early-adopters of QIS technologies. One of the goals of this working group is to help other government agencies understand QIS opportunities and to develop potential applications. This IWG, in coordination with the Science IWG, led the joint Quantum Sensor activity in the spring of 2021.
- NIH, which co-chairs the End-Users IWG, released a Notice of Special Interest that includes Quantum Computing with the purpose of informing potential applicants to the National Institute on Drug Abuse (NIDA) of NIDA's interest in grant applications that will develop or utilize advanced computational approaches to describe complex drug-disease relationships in ways that will rapidly advance the development of new treatments, allow for targeted funding of substance use disorder (SUD) drug discovery and improve health care.
- The *National Strategic Overview for QIS* and the NQI Act identified consortia as mechanisms to foster emerging technologies by growing the market, prioritizing pre-competitive research needs, and establishing norms and standards. NIST establish the QED-C,[163] as legislated in the NQI Act and in FY 2020, NIST used 70% of the new funds provided by Congress to support this engagement. NIST and DOE continue to provide oversight via active seats on the QED-C Steering Committee.

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[159] https://www.usaeop.com/
[160] https://ndseg.sysplus.com/
[161] https://www.quantum.gov/wp-content/uploads/2021/10/2021_NSTC_ESIX_INTL_TALENT_QIS.pdf
[162] https://www.whitehouse.gov/ostp/news-updates/2021/10/07/readout-of-white-house-summit-on-quantum-industry-and-society/
[163] https://quantumconsortium.org/

- SBIR/STTR programs operated by several SCQIS Agencies (including NASA, NSF, DOE, and DOD) provide direct seed funding to startups and small businesses in the quantum technology economic sector to support critical R&D activities, such as improved management of quantum-classical interfaces, and enhanced quantum control capabilities.
- DOE National Labs continue to leverage CRADAs to facilitate industry participation in SC-sponsored basic research QIS projects.
- I-Corps programs help university researchers explore entrepreneurial opportunities and understand the potential economic impacts of new scientific capabilities.
- The NSF Convergence Accelerator program added a Quantum Technology track in FY 2020 to explore near term use-cases for QIS in society; this builds upon three workshops hosted by NSF in FY 2019. The Convergence Accelerator requires teams to leverage public-private and other types of partnerships to rapidly transition research outputs into practical quantum technologies.
- In FY 2020, NSF began offering supplements to research teams to support graduate-student work on industry-based quantum computing cloud platforms, at no financial cost to academic researchers.
- To facilitate technology transfer and to enable innovations, the DOE National QIS Research Centers portfolio integrates the QIS science and technology chain (fundamental science-devices-systems-prototypes-applications) to accelerate progress from discovery to prototypical technology and applied research, through coupled co-design approaches. With the participation of 14+ industry partners, the Centers forge connectivity among industry, DOE national labs and academia. They also play a major role in incentivizing start-ups. For instance, Q-NEXT (one of the five Centers) participates in the DUALITY quantum accelerator program for startups focused on building quantum technology products, applications and enabling technologies.

4.4 Providing Critical Infrastructure

Scientific infrastructure accelerates the cycle of progress from discovery and exploration to technology development by providing key shared technical and scientific capabilities to a larger community. QIS requires increasingly complex experimental and technical systems as researchers carry out more sophisticated efforts. New applications and new lines of inquiry with extraordinarily fragile quantum states require platforms with specialized materials, exacting tolerances, ultralow temperatures, and new quantum control systems. Building upon investments made in other contexts such as nanotechnology and semiconductor development, additional investments in infrastructure can catalyze progress and enable scientific and technical breakthroughs that would not otherwise occur.

Infrastructure also draws together collaborations and teams that require certain equipment or facilities to carry out their R&D enterprises. Hence, the research community, as well as the operational systems for quantum information processing, can be profoundly influenced by early planning and investment in infrastructure, transforming the realm of the possible by distributing costs and maintaining key knowledge, staff, and abilities in centralized facilities. Activities to support the identification and development of infrastructure include:

- The NSF Institutes and DOE Centers highlighted in Box 3.4 and Box 3.6 represent a major investment in infrastructure for the NQI.
- NASA AMES has augmented infrastructure to allow testing of a Quantum Annealer, while the Space Technology Mission Directorate has made investments that will enable or enhance future NASA missions and applications to other government agencies and the commercial sector.

- NSF sponsored a workshop focused on the intersection of nanofabrication and QISE and a workshop on advancing quantum systems for computing, communications, and sensing applications.[164,165]
- NSF is providing scientists with access to research infrastructure and instrumentation across several scales to enable R&D in QISE and quantum materials, through targeted NSF investments and industry and interagency partnerships. This effort includes coordination with industry partners in FY 2020 and beyond to provide academic researchers with access to industry-based quantum computing cloud platforms, supporting investments in the Software-Tailored Architecture for Quantum co-design project, and supporting mid-scale infrastructure for rapid prototyping and development of quantum materials and devices through the NSF Q-AMASE-i program foundries and the National Nanotechnology Coordinated Infrastructure (NNCI) program.
- DOE continues to expand support for its Nanoscale Science Research Centers to maintain development of new QIS tools and materials and to provide access to early quantum technologies through its quantum testbed programs. In addition, DOE's Oak Ridge National Laboratory is providing access to current quantum computers through its Quantum Computing User Program.
- NIST helped launch the Boulder Cryogenic Quantum Testbed where researchers can probe and compare the performance of dielectric materials useful for QIST.[166]
- LPS launched the Qubit Collaboratory quantum center.
- In fulfillment of the FY 2020 NDAA, the DOD has announced two quantum centers, one at NRL and one at AFRL.

4.5 Maintaining National Security and Economic Growth

The *National Strategic Overview for QIS* recommends a comprehensive approach to ensure that the economic and security benefits of QIS and technology are realized by the United States as scientific discoveries and technological opportunities emerge. This strategy includes maintaining awareness and agility, developing the market for QIS technologies, using government-wide coordination mechanisms, and maintaining appropriate approaches to intellectual property and regulation. Actions listed below support these policy goals.

- The ESIX Subcommittee provides a forum to address economic and national security issues.
- Industry consortia such as the QED-C, with leadership from NIST, DOE and DOD, provide a forum to address concerns regarding the market for emerging technologies. The QED-C has a Quantum for National Security, or Q4NS, technical advisory committee to tackle many of these pressing issues from the industry side.
- DOS is actively working with international partners to protect sensitive quantum technologies.
- NIST, as part of the Department of Commerce, engages directly with industries via CRADA arrangements that focus on technology transfer.
- Post-quantum cryptography (PQC), also known as quantum-resistant cryptography, includes measures such as updating cryptographic protocols and standards. PQC research and implementation activities are supported by several SCQIS agencies including NIST, NSF, DOD, DHS, and NSA.

[164] https://www.cnf.cornell.edu/events/nsf-nnci-quantum
[165] https://sites.duke.edu/qdsworkshop/
[166] https://www.colorado.edu/today/2019/10/03/new-boulder-facility-help-pave-way-quantum-computers

- NSA emphasized the importance of PQC (see Box 4.1) and provided a list of Post-Quantum Cybersecurity Resources[170] and a FAQ on quantum computing and post-quantum cryptography.[167]
- NSA does not recommend the usage of quantum key distribution and quantum cryptography for securing the transmission of data in National Security Systems (NSS) unless certain limitations are overcome.[168]
- Through its Office of Technology Transitions, DOE is organizing several Quantum Innovation Xlab events to promote exchange of information and ideas between industry, universities, investors, and end-use customers with lab innovators and experts.
- Through its Isotope Program, DOE invests in technology development for the enrichment and production of isotopes critical to QIS R&D, reducing the Nation's dependence on foreign resources.
- The NSF Q-AMASE-i program requires the foundries to intertwine industry partners closely with foundry operations and technological development activities in order to accelerate the development of the Nation's quantum technologies economic sector.
- Atomic clocks have historically been a sizable market for quantum technology. Atomic clocks with enhanced stability and deployment capabilities can have significant national security impacts, providing resiliency and continued operations in GPS-denied environments.

Box 4.1

Quantum Resistant Encryption

Post-Quantum Cryptography (PQC) standards[169] coordinated by NIST (Section 3.1) will identify one or more quantum-resistant public-key cryptographic algorithms for commercial and general usage. This is motivated by the need to establish security protocols for classical communication channels (e.g., today's internet) that can remain secure even after the development of a utility-scale quantum computer.

In a public statement,[170] the National Security Administration (NSA) wrote, "we thank NIST for all their efforts to help advance the adoption and deployment of secure post-quantum cryptography, which are vital to the defense of our nation." To describe challenges for adopting post-quantum cryptographic algorithms, NIST released its whitepaper 'Getting Ready for Post Quantum Cryptography',[171,172] and NSA released an update to its *Quantum Computing and Post-Quantum Cryptography Frequency asked Questions*.[167] The Department of Homeland Security (DHS) is also partnering with NIST to provide relevant stakeholders guidance on transition to post-quantum cryptography.[173]

167 https://media.defense.gov/2021/Aug/04/2002821837/-1/-1/1/Quantum_FAQs_20210804.PDF
168 https://www.quantum.gov/nsa-cybersecurity-perspectives-on-quantum-key-distribution-and-quantum-cryptography/
169 https://csrc.nist.gov/Projects/post-quantum-cryptography
170 https://www.nsa.gov/Cybersecurity/Post-Quantum-Cybersecurity-Resources/
171 https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.04282021.pdf
172 https://www.quantum.gov/nist-releases-whitepaper-on-the-challenges-with-adopting-post-quantum-cryptographic-algorithms/
173 https://www.dhs.gov/quantum

4.6 Advancing International Cooperation

Scientific knowledge transcends national boundaries. International collaboration accelerates discoveries and provides an avenue to deepen relationships between nations. These relationships provide a platform to establish trust, to facilitate communication, and to demonstrate shared principles through the conduct of research and education. QIS R&D is deeply international, with talent, infrastructure, and industrial capabilities globally diffused. As of 2021, about three dozen countries around the world have significant government funding for QIS research, and at least 17 have national strategies for quantum technology development.[174] Accordingly, it is U.S. policy to promote and support international cooperation on QIS research and skills development, especially in ways that affirm principles of scientific rigor and research integrity, freedom of inquiry, merit-based competition, openness, transparency, and others.[175] By enhancing cooperation with those who share these foundational principles and values, we can ensure that capabilities in the United States and our close allies and partners in QIS remain strong in order to foster a vibrant and secure international QIS ecosystem.

International collaboration is facilitated through a number of mechanisms. For instance, bilateral agreements between U.S. agencies and their international counterparts enable benefits such as a coordinated review process, reciprocal or joint funding, and student and researcher exchange to the benefit of both parties. Some agencies, pursuant to their mission and authorities, can also pursue unilateral support for international research collaborators. Informal engagements with universities and industry are also essential to connect government, academic, and private sector stakeholders. Through these collective approaches, a large number of federally-funded QIS research projects and initiatives continue to enjoy international collaborators, resulting in coordinated efforts with mutual benefits.

Actions to encourage and enhance international cooperation on QIS are highlighted here. Specifically, these actions support the policy goals to expand the discovery space, increase the global talent pool, and grow the marketplace for QIS concepts and technologies.

- As QIS is a priority emerging technology of the United States, pathways to explore enhanced cooperation were raised at several high-level meetings:
  - A White House press release regarding a vision for a new Atlantic Charter cited the United States' and the United Kingdom's intention to strengthen cooperation in science and technology areas including quantum technologies.[176]
  - At the April 2021 Summit between President Joseph Biden and Prime Minister Suga Yoshihide, the leaders highlighted bilateral quantum cooperation, which was also included in the announcement of the U.S.-Japan Competitiveness and Resilience Partnership.[177,178]

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[174] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf
[175] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[176] https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/10/joint-statement-on-the-visit-to-the-united-kingdom-of-the-honorable-joseph-r-biden-jr-president-of-the-united-states-of-america-at-the-invitation-of-the-rt-hon-boris-johnson-m-p-the-prime-min/
[177] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/16/u-s-japan-joint-leaders-statement-u-s-japan-global-partnership-for-a-new-era/
[178] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/16/fact-sheet-u-s-japan-competitiveness-and-resilience-core-partnership/

  - In a joint statement by the White House and the Republic of Korea, President Biden and President Moon committed to explore a future-oriented partnership by leading innovation in several areas including quantum technology.[179,180]
- The SCQIS and OSTP coordinate with DOS on opportunities for enhanced international cooperation in QIS. These have included quantum cooperation statements that articulate shared visions for the promotion of collaborative research efforts, enhancement of training opportunities, and growth of a global quantum market:
  - The United States and the United Kingdom signed a *Joint Statement on Cooperation in Quantum Information Sciences and Technologies* in furtherance of a shared goals for the development of QIST.[181,182]
  - The United States partnered with Australia on a Joint Statement on Cooperation in Quantum Science and Technology in order to strengthen ongoing collaboration between the two countries.[183,184]
  - Building on the Tokyo Statement on Quantum Cooperation,[185] the United States and Japan have continued to engage through a series of meetings and agreements. The 16th Japan-U.S. Joint Working-Level Committee (JWLC) Meeting on Science and Technology Cooperation took place online on June 17th, 2021.[186] During the meeting, quantum technologies were a topic of discussion. The JWLC featured the signing of a project arrangement on quantum information science between the Ministry of Education, Culture, Sports Science and Technology of Japan (MEXT) and the U.S. DOE.
- U.S. QIS activities are distributed across several agencies, each pursuing QIS mission-specific collaborations, unilaterally or in partnership with additional agency partners.
  - The Secretary of State visited the joint University of Copenhagen-Microsoft Center for Quantum Devices in Denmark to meet with Danish QIS stakeholders and explore opportunities for enhanced engagement.
  - On June 7, 2021, DOE signed an MOU with Denmark on clean energy research, including exploring the use of QIS technologies in pursuit of new green technologies.[187]
  - The interim United States-Republic of Korea Senior Economic Dialogue in July included a discussion on enhancing QIS cooperation, ahead of the main meeting in the Fall.
  - The AFRL spearheaded several international collaborations including a joint US/AFOSR-Korea QIS Initiative[188] that capitalizes on a 14-year partnership with the Republic of Korea and a joint US/AFOSR-Taiwan Quantum and Nano-Materials Initiative that enhances a 17-year international partnership.

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[179] https://www.whitehouse.gov/briefing-room/statements-releases/2021/05/21/u-s-rok-leaders-joint-statement/
[180] https://www.whitehouse.gov/briefing-room/statements-releases/2021/05/21/fact-sheet-united-states-republic-of-korea-partnership/
[181] https://www.state.gov/cooperation-in-quantum-information-sciences-and-technologies-uk
[182] https://www.whitehouse.gov/ostp/news-updates/2021/11/04/the-united-states-and-united-kingdom-issue-joint-statement-to-enhance-cooperation-on-quantum-information-science-and-technology/
[183] https://www.state.gov/cooperation-in-quantum-science-and-technology-aus
[184] https://www.whitehouse.gov/ostp/news-updates/2021/11/18/the-united-states-and-australia-partner-to-build-quantum-future/
[185] https://www.state.gov/tokyo-statement-on-quantum-cooperation/
[186] https://www.state.gov/the-16th-japan-u-s-joint-working-level-committee-meeting/
[187] https://www.energy.gov/articles/secretary-granholm-danish-climate-energy-and-utilities-minister-jorgensen-establish
[188] https://www.quantum.gov/afosr-international-qis-funding-oppurtunity/

- The AFRL held its 3rd annual Quantum Information Science international workshop that virtually hosted 600 registrants from 31 countries.
- The AFRL is participating in a Position, Navigation, and Timing (PNT) TTCP Strategic Challenge with the Five Eyes partners focused on navigation in GPS-denied and contested environments. The effort includes quantum-assisted PNT technologies and AFRL is contributing clocks, a cold atom accelerometer, and PNT integrating architecture. The USPACOM RIMPAC 2022 will host the final demonstration of the resulting technologies on a New Zealand naval ship in the summer of 2022.
- ARO leads U.S. efforts in the U.S.-Australia MURI collaboration in quantum sensing and control. Australia's Department of Defense extended funding for the Australian team participation by two years.[189]
- NIST participates in the development of international standards in QIS technologies. In addition, the QED-C has a technical advisory committee (TAC) focused on standards development in the international arena. Members of the TAC participate in relevant standards development organizations worldwide.
- NIST, in coordination with the SCQIS and DOS, is helping to develop an option for international companies to participate in the QED-C.
- NSF announced a Dear Colleague Letter (DCL) on International Collaboration Supplements in Quantum Information Science and Engineering Research. The DCL invites requests for supplemental funding from existing QIS research awardees to add a new — or strengthen an existing — international dimension to their award. On June 22, 2021, AFRL and AFOSR hosted their 3rd annual International QIS Workshop.

[189] https://www.defenceconnect.com.au/key-enablers/8282-defence-extends-funding-for-high-profile-quantum-computing-project

5 Summary and Outlook

The timeline in Figure 5.1 summarizes some key events for the establishment and implementation of the National Quantum Initiative.

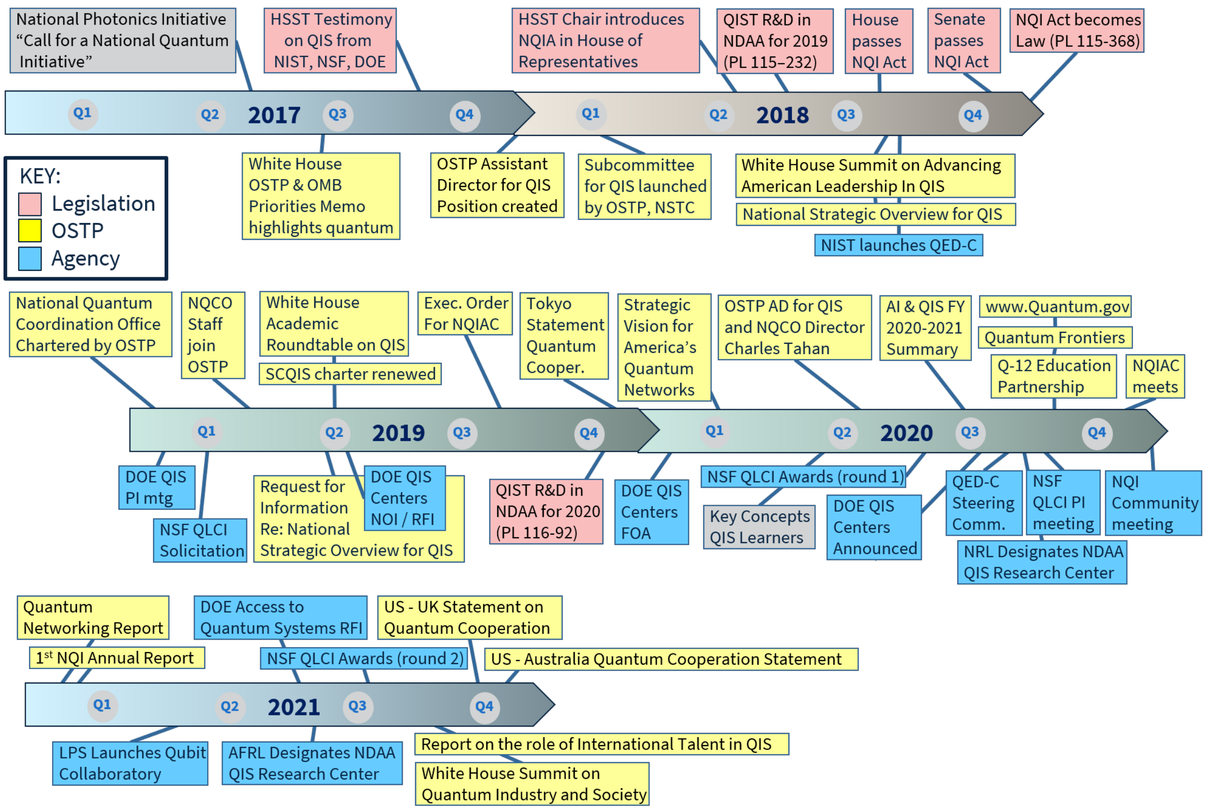

Figure 5.1: Timeline of actions establishing and implementing the NQI. Color-coding shows legislative process in red; OSTP and NSTC actions in yellow; Agency actions in blue. The NQI was introduced in Congress, passed in the House, passed in the Senate, and signed into law by the President, reflecting bipartisan support. The National Defense Authorization Act (NDAA) for FY 2019 and FY 2020 are shown on the timeline because they authorize QIST R&D supported by DOD. Selected actions led by the White House OSTP and the NSTC Subcommittee on QIS are highlighted in yellow. Agency actions on QIS R&D have been ongoing during this whole time. Selected NQI-authorized activities are highlighted here in blue, notably to establish consortia and centers called for by the NQI Act.

The NQI Act calls for a 10-year NQI Program, with an assessment of U.S. leadership in QIS after five years and an updated strategic plan at that time. To support the NQI Program development, implementation, and planning, the budget data and programmatic overview provided in this annual NQI Supplement to the President's Budget is an important step. Looking forward, the SCQIS and ESIX, with support from the NQCO and information from the NQI Advisory Committee, will work to identify the most important metrics to chart progress towards NQI Program goals and priorities. As the landscape evolves, the Subcommittees will develop new policies and update current ones to ensure activities are in alignment with the current and future needs of the QIS ecosystem. By continuing to support investment in fundamental QIS across agencies, the United States will be positioned to capitalize on scientific advancements in this emerging area for economic prosperity, national security, and the betterment of the American people.