NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2024 BUDGET

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

December 2023

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The NSTC Subcommittee on Quantum Information Science (SCQIS) was established 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 2024 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
FFRDC	Federally Funded Research and Development Center
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
NDAA	National Defense Authorization Act
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
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
PQC	Post-Quantum Cryptography
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QIST	Quantum Information Science and Technology
QLCI	Quantum Leap Challenge Institute
R&D	Research and Development
SCQIS	Subcommittee on Quantum Information Science
USPTO	United States Patent and Trademark Office
USDA	United States Department of Agriculture

Executive Summary

Quantum information science (QIS) is a unification of quantum mechanics and information theory, two foundational fields underpinning modern technology. Together, these fields are producing transformative new types of computers, sensors, and networks, with the potential to advance the Nation's prosperity and strengthen its security. Investments in fundamental QIS research will lay a foundation for technologies of the future and open new frontiers in science. The Biden-Harris administration is committed to advancing critical and emerging technologies, including QIS, as reaffirmed in the Multi-Agency Research and Development (R&D) Priorities for the Fiscal Year (FY) 2025 Budget memorandum.

> *"Quantum computing has the potential to transform everything, from how we create new medicines to how we power artificial intelligence and cybersecurity. It's technology that is vital to our economy and equally important to our national security." – President Biden*

The National Quantum Initiative (NQI) Act was enacted in December 2018 to accelerate American leadership in QIS technology. The NQI Act authorizes U.S. Federal departments and agencies (hereafter, "agencies") to establish centers and consortia and carry out new programs to foster QIS R&D. It calls for the coordination of QIS R&D efforts across the Federal Government, as well as with industry and the academic community.

FY 2024 marks a critical juncture for the NQI program as several of the initial authorizations from the NQI Act expire after five years. In June 2023, the NQI Advisory Committee published its first assessment of the NQI Program and made recommendations for enhancements to the program, and the House Committee on Science, Space, and Technology held a full hearing on Advancing American Leadership in Quantum Technology. During the hearing, the Committee referenced the NQI Advisory Committee report, which recommended that the NQI Act be reauthorized for at least the next five years.

This is the fourth annual report on the NQI Program and budget, as required by Section 103(g) of the NQI Act. The report describes investments in the NQI Program that build upon the establishment of NQI centers, the Quantum Economic Development Consortium, and new QIS R&D activities. Agencies reported budget expenditures for QIS R&D of $449 million in FY 2019, $672 million in FY 2020, $855 million in FY 2021, and $1,031 million in FY 2022, followed by $932 million of enacted budget authority for FY 2023, and a requested budget authority of $968 million for FY 2024.

In line with the *National Strategic Overview for QIS*, the United States is making substantial and sustained investments in QIS R&D to explore a wide range of applications and nurture a culture of discovery. Major efforts funded by several agencies are described in Section 3 of this report, and Section 4 contains overviews of NQI activities organized by QIS policy areas, such as investing in fundamental science and engineering, workforce development, industry engagement, infrastructure investments, economic and national security, and encouraging international cooperation.

QIS could have profound positive impacts on society and the way each agency accomplishes its mission. Recognizing the importance of a quantum workforce that is diverse, inclusive, and reflects the whole of society, agencies are prioritizing efforts to ensure that all Americans have the opportunity to benefit from participation in QIS. Furthermore, while the development of QIS technologies is at an early stage, now is a critical time to develop the fundamental scientific knowledge, infrastructure, and workforce needed for the creation of new applications for QIS-inspired technologies, grow the marketplace, and foster an ecosystem for basic, applied, and translational research in QIS.

1 Introduction

Quantum information science (QIS) builds on quantum mechanics and information theory to explore applications in computation, networking, and measurement. The improved understanding of quantum effects provided by these explorations shows that, in some cases, the performance of quantum information technologies can be vastly superior to that of traditional, classical technologies. Building on key QIS discoveries since the 1980s, pioneering QIS experiments since the 1990s, growth in quantum engineering capabilities since the 2000s, 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 U.S. Government to enact the National Quantum Initiative (NQI) Act, accelerating QIS research and development (R&D) and training opportunities.[1]

Box 1.1

COORDINATING BODIES SUPPORTING THE NATIONAL QUANTUM INITIATIVE

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

The Subcommittee on Economic and Security Implications of Quantum Science (ESIX) of the NSTC is co-chaired by OSTP, the Department of Defense (DOD), DOE, and the National Security Agency (NSA). In parallel with the SCQIS, ESIX 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 R&D policy.

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal advisory committee called for in the NQI Act to advise the President, SCQIS, and ESIX, as well as provide independent assessments of the NQI Program and make recommendations for the President to consider when reviewing and revising the NQI Program. The NQIAC is comprised of leaders in QIS from industry, academia, and the Federal laboratories. In 2022, an Executive Order on Enhancing the National Quantum Initiative Advisory Committee reconstituted the NQIAC as a Presidential advisory committee.

The National Quantum Coordination Office (NQCO) is located in OSTP within the Executive Office of the President to carry out the daily activities needed for coordinating and supporting the NQI Program. The NQCO is tasked with providing technical and administrative support to the SCQIS, ESIX, and the NQIAC, overseeing interagency coordination of the NQI Program, serving as the point of contact on Federal civilian QIS 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, and the staff are listed in the front matter.

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." The NQI Act authorizes NIST, NSF,

[1] National Quantum Initiative Act (hereinafter "NQI Act") (Pub. L. 115-368), 15 U.S.C. § 8801 et seq. For the NQI Act with amendments made as of October 2022, see https://www.quantum.gov/wp-content/uploads/2022/08/NQIA2018-NDAA2022-CHIPS2022.pdf

and DOE to strengthen and expand QIS programs, centers, and consortia. The NQI Act also calls for the coordination of QIS R&D efforts across the U.S. Government, including the civilian, defense, and intelligence sectors. To guide these actions, the NQI Act legislates several responsibilities for the SCQIS, NQCO, and NQIAC.

Concurrently, the Defense Quantum Information Science and Technology (QIST) R&D Program,[2] as established and modified by the fiscal year (FY) 2019 and FY 2020 National Defense Authorization Acts (NDAAs),[3,4] respectively, continues DOD's three-decade history of QIS R&D. The FY 2022 NDAA amended the NQI Act to codify ESIX, and also legislated specific responsibilities to the Subcommittee.[5]

The CHIPS and Science Act of 2022 further amended the NQI Act, authorizing additional activities for NIST, DOE, and the SCQIS.[6] Altogether, the NQI Program provides an overarching framework to strengthen and coordinate QIS R&D activities across agencies, industry, and the academic community. See Box 1.1 for an overview of the different coordination mechanisms.

Some authorizations from the NQI Act expired at the end of FY 2023, such as the authorizations for the NSF Multidisciplinary Centers for Quantum Research and Education (section 302) and the DOE National QIS Research Centers (section 402). On June 7, 2023, the House of Representatives Committee on Science, Space, and Technology (HSST) held a full committee hearing on Advancing American Leadership in Quantum Technology to evaluate the state of QIS research, development, and technology in the United States. The hearing served as an opportunity to review and discuss the first five years of the NQI Act, the economic value of QIS and its applications, the national security importance of developing QIS capabilities, and what policies and legislation should be considered for the next five years. More information about the hearing, including the hearing's charter, written statements, and a video recording are available at the hearing's webpage.[7]

Figure 1.1: Witnesses at the HSST Hearing on Advancing American Leadership in Quantum Technology

[2] As described in the NQI Act, "quantum information science" means the use of the laws of quantum physics for the storage, transmission, manipulation, computing, or measurement of information. QIST refers to technologies that leverage QIS

[3] John S. McCain National Defense Authorization Act for Fiscal Year 2019 (Pub. L. 115–232) § 234, 10 U.S.C. § 2358 note

[4] National Defense Authorization Act for Fiscal Year 2020 (Pub. L. 116-92) §220

[5] National Defense Authorization Act for Fiscal Year 2022 (Pub. L. 117-81) § 6606 (amending the NQI Act to add a new section 105), 15 U.S.C. § 8814a

[6] Research and Development, Competition, and Innovation Act (division B of the law commonly referred to as the CHIPS and Science Act (Pub. L. 117-167)) §§ 10661 and 10104(b) (amending NQI Act to add new sections 103(h), 201(a)(3)-(5), and 403-404), 15 U.S.C. §§ 8813(h), 8831(a)(3)-(5), and 8853-8854

[7] https://science.house.gov/2023/6/full-committee-hearing

Box 1.2

The NQIAC Publishes First Assessment of the NQI

Figure 1.2: The NQIAC and the NQCO

The National Quantum Initiative Advisory Committee (NQIAC) was legislated by the NQI Act to advise the President, the SCQIS, and ESIX and make recommendations for the President to consider when reviewing and revising the NQI Program. The NQIAC is also tasked with submitting reports to the President and appropriate committees of Congress with their independent assessment of the NQI Program, including recommendations for improvements. The NQIAC consists of QIS leaders from industry, academia, the Federal government, and the Federal laboratories.

After being elevated to a Presidential advisory committee, the NQIAC had its first meeting in December 2022. Three NQIAC subcommittees worked for the next six months, hearing from agencies and subject-matter experts across the field. Then in June 2023, the NQIAC published its first assessment of the NQI Program, including recommendations for enhancements to the Program. Their report, titled *Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science*,[8] identifies three findings, four overarching recommendations, and nine detailed recommendations, which are listed on quantum.gov.[9]

The *National Strategic Overview for QIS* recommends strengthening the United States' approach to QIS R&D by focusing on six policy areas: science, workforce, industry, infrastructure, security, and international cooperation.[10] The Overview and these six policy pillars have been augmented by additional reports and plans, building upon Federal QIS R&D coordination via interagency activities such as those described in the 2009 NSTC Report on *A Federal Vision for QIS*,[11] the 2016 NSTC Report on

[8] https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf
[9] https://www.quantum.gov/nqiac-report-on-renewing-the-national-quantum-initiative/
[10] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[11] https://www.quantum.gov/wp-content/uploads/2020/10/2009_NSTC_Federal_Vision_QIS.pdf

Advancing QIS,[12] and ongoing interagency working group activities of the SCQIS and ESIX. The U.S. QIS R&D efforts are also informed by numerous Federally-funded workshops led by the QIS R&D community. Many of these reports are available at quantum.gov.[13]

Key activities and the Federal budgets used to support these efforts are reported in the NQI's annual reports. Mechanisms to strengthen core programs and coordinate QIS R&D efforts across the Federal Government are also described, as is progress made by the quantum consortium, centers, and institutes established as part of the NQI.

[12] https://www.quantum.gov/wp-content/uploads/2020/10/2016_NSTC_Advancing_QIS.pdf
[13] https://www.quantum.gov/publications-and-resources/publication-library/

2 Budget Data

The U.S. Federal budgets for QIS R&D presented here summarize FY 2019 – FY 2022 actual expenditures, FY 2023 estimated expenditures, and FY 2024 proposed budget requests. The U.S. QIS R&D budgets have roughly doubled since FY 2019, with efforts catalyzed by the NQI Program.

Figure 2.1 shows overall Federal budgets for U.S. QIS R&D activities aggregated across several agencies including NIST, NSF, DOE, DOD, the Department of Homeland Security (DHS), and the National Aeronautics and Space Administration (NASA). Much of the growth in QIS R&D budgets is for NQI activities such as the establishment of a quantum consortium by NIST, the NSF Quantum Leap Challenge Institutes (QLCIs), the DOE National QIS Research Centers, and the coordination and strengthening of core QIS programs across many agencies. Sustained growth in U.S. QIS R&D will position American universities, industry, and Government researchers to explore quantum frontiers, advance QIS technologies, and develop the required workforce to continue American leadership in this field and the related industries of the future.

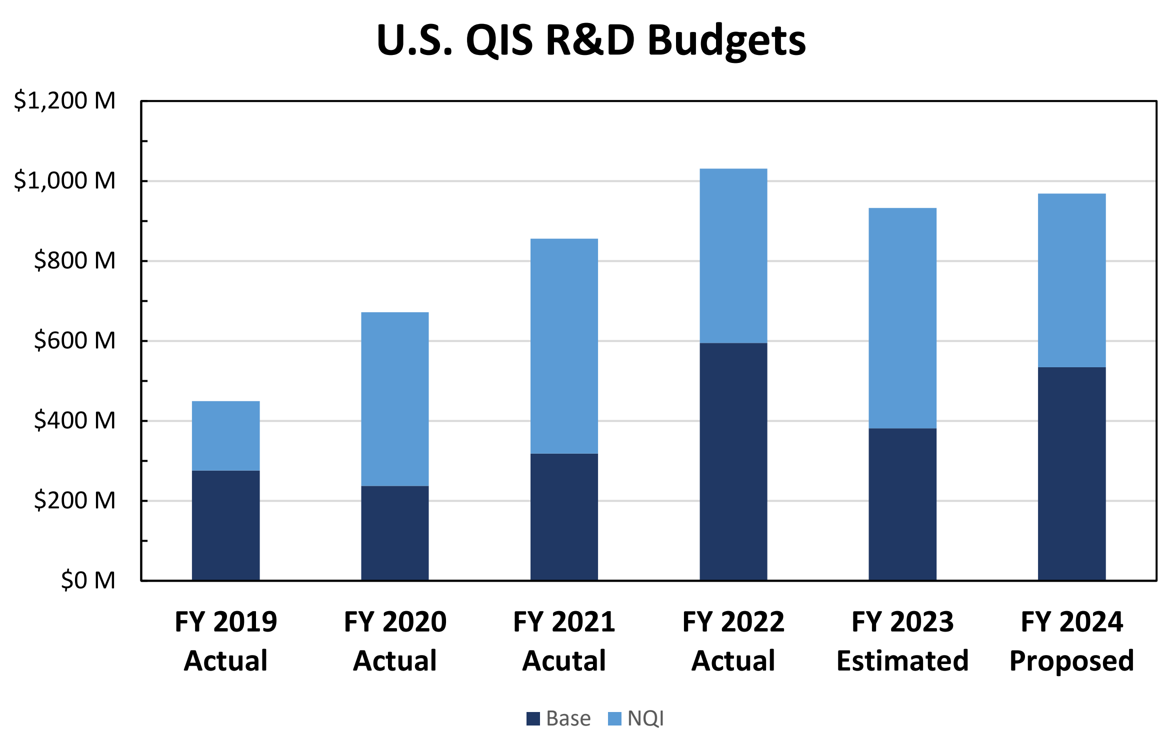

Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQI Act. The bar heights represent the total budget for each fiscal year (FY 2019 – FY 2022 actual expenditures, FY 2023 estimated expenditures, and FY 2024 budget requests). The portion of each bar marked "NQI" identifies funding allocated for NQI Act-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities.

Budget distributions over five different NQI Program Component Areas (PCAs) are discussed below. These PCAs are used by the Office of Management and Budget (OMB) to collect and analyze budget data, and they are consistent with the classification introduced in the *National Strategic Overview for QIS* and those in the previous Annual Reports 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. QSENS 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-analog computing, as well as quantum-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 technologies for QIST 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 (PQC).

Figure 2.2 shows budget allocations by NQI PCA for FY 2019 – FY 2024 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, with Figure 2.3 showing 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 Figure 2.1 – Figure 2.3 present budget portions for NQI Act-authorized activities, NQI PCAs, and selected agencies. The data show an increased and sustained 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.

The NQCO does not have an operating budget, and therefore the NQCO is not directly accounted for in the budget data presented in this section. The NQCO is staffed by non-reimbursable details from NQI Act agencies. To date, DOD, DOE, NIST, NSA, and NSF have detailed staff to the NQCO.

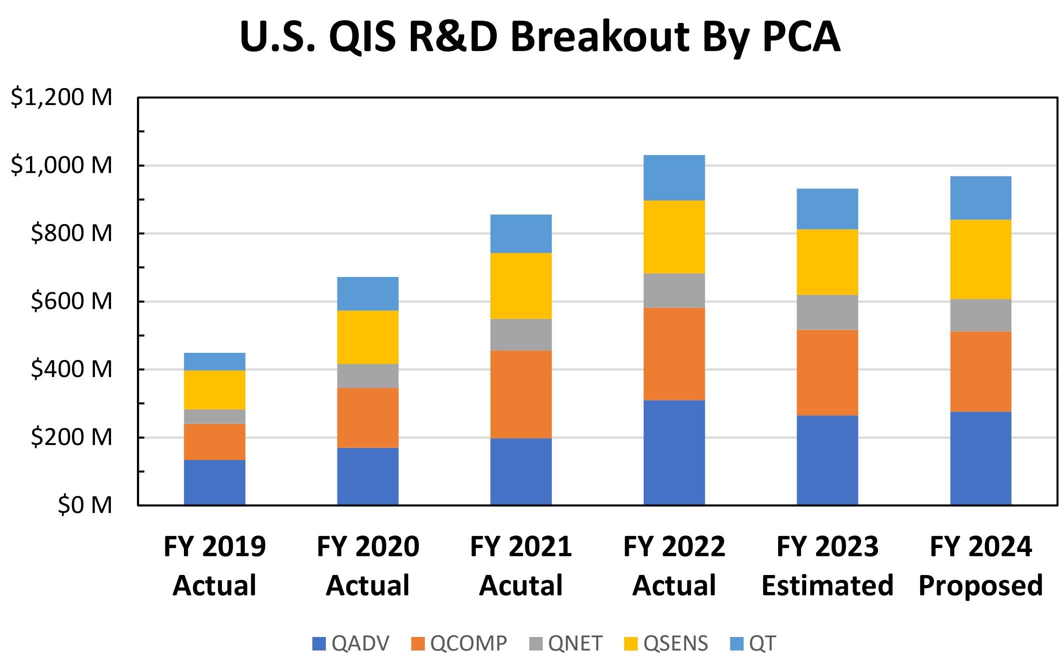

Figure 2.2: U.S. QIS R&D Budget allocations by NQI Program Component Area (PCA) for FY 2019 – FY 2022 actual expenditures, FY 2023 estimated expenditures, and FY 2024 budget requests.

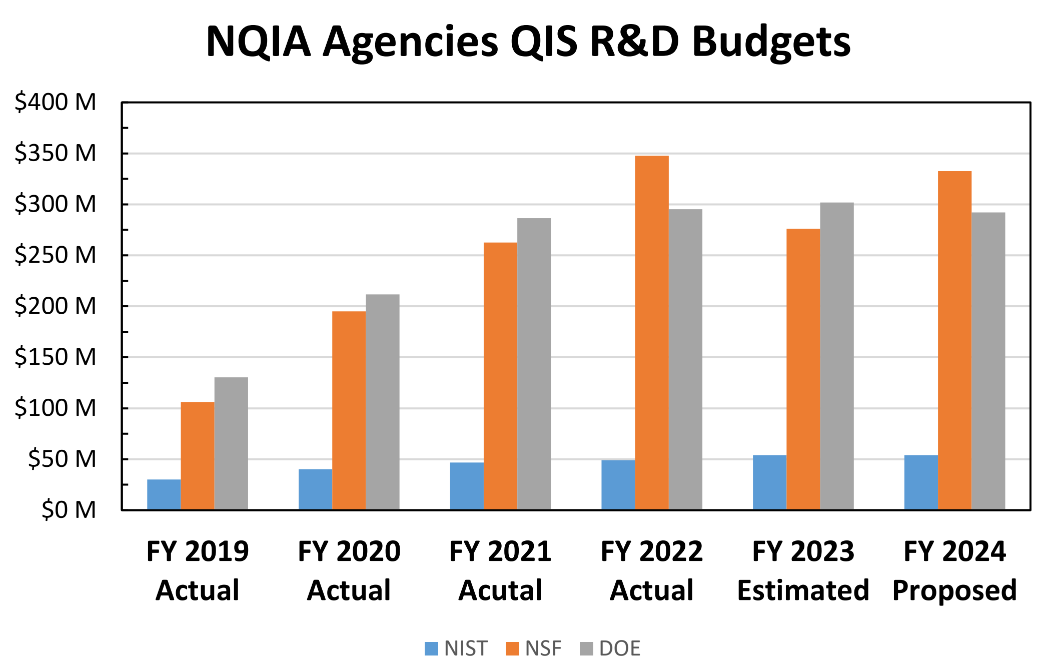

Figure 2.3: QIS R&D Budgets for three agencies identified in the NQI Act, showing FY 2019 – FY 2022 actual expenditures, FY 2023 estimated expenditures, and FY 2024 budget requests.

The next sections describe how agencies are using these budgets to advance QIS 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 NQI provides a framework to strengthen and coordinate QIS R&D activities across Federal agencies. The NQI also promotes engagements with industry, the academic community, National Laboratories, and Federally Funded Research and Development Centers (FFRDCs). As illustrated in Figure 2.4, investments made in fundamental QIS research, education, training, and workforce development across agencies are reinforcing and complementary, strengthening their collective efforts. The resulting ecosystem accelerates American leadership in QIS by simultaneously promoting discovery, exploration, and efforts to develop the market, supply chain, infrastructure, and the capacity to utilize quantum technologies.

In Section 3, QIS R&D programs at selected agencies are summarized, and Section 4 tracks progress on key policy topics identified in the *National Strategic Overview for QIS*.

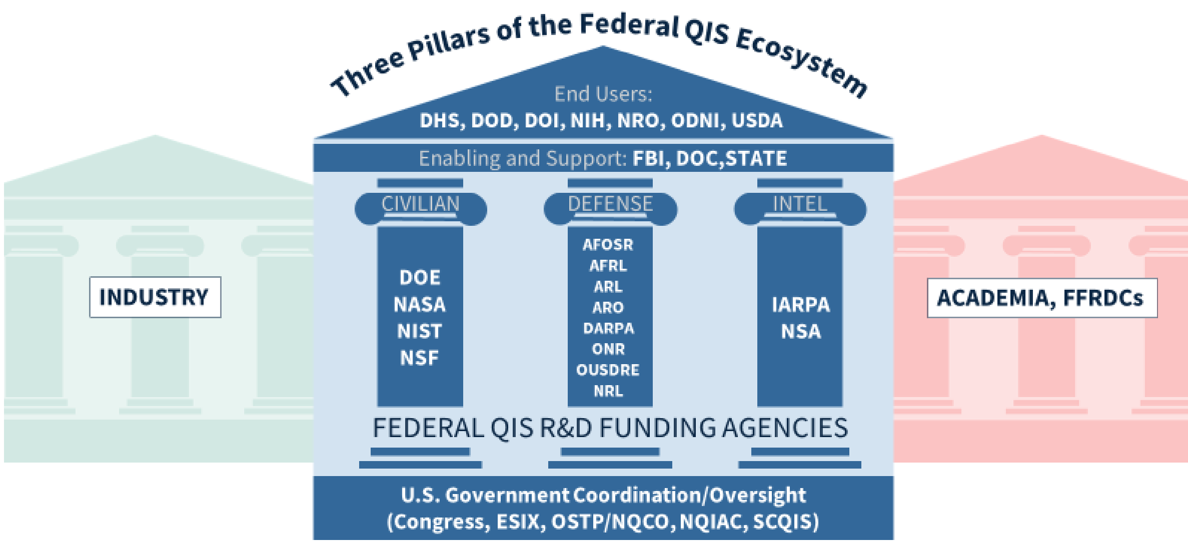

Figure 2.4: Federal QIS R&D funding agencies can be seen as three pillars that support the Federal QIS ecosystem. Civilian science agencies (DOE, NASA, NIST, NSF) stand alongside DOD science agencies (AFOSR, AFRL, ARL, ARO, DARPA, OUSD(R&E), ONR, NRL) and the IC science agencies (IARPA, NSA) to collectively support QIS R&D efforts. Within the Federal Government, support enabling the QIS ecosystem also comes from DOC (BIS, EDA, ITA, USPTO), FBI, and DOS, and potential end users including DHS, DOD, DOI, NIH, NOAA, NRO, ODNI, and USDA. Authorization, coordination and oversight are provided by Congress, the SCQIS, ESIX, OSTP, the NQCO, and the NQIAC. Pictured here as separate houses, Industry, Academia, and FFRDCs are also critically important for QIS R&D.

3 QIS R&D Program Highlights

This section describes QIS R&D activities by agency, including NIST, NSF, DOE, DOD, NASA, the NSA Laboratory for Physical Sciences (LPS), and the Intelligence Advanced Research Projects Activity (IARPA), to provide a more complete description of the U.S. QIS R&D enterprise. Each agency works independently on its respective mission. Yet, the collection of efforts is crucial for American leadership in QIS. With activities coordinated through coherent policy goals, the combined set of activities described here accelerates the exploration of basic science, 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 of agency programs. In many cases, the results are fueled by the support of multiple agencies.

Box 3.1

Highlight: High-Fidelity Quantum Logic Operations with Silicon Qubits

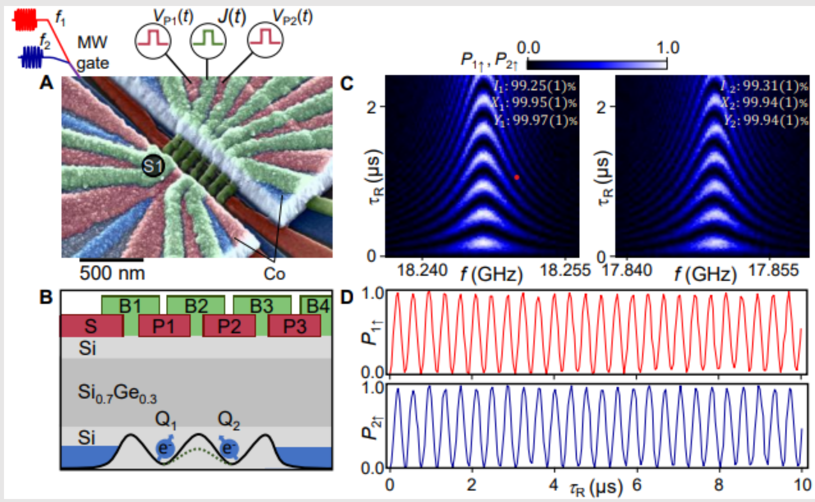

Figure 3.1. (Left) Quantum dots trapping electron spin qubits in a silicon-germanium heterostructure. (Right) Observation of spin qubit operations.[14]

Solid state platforms offer scalable approaches to quantum information processing. Advances in materials science and fabrication, as well as the control and detection of spins in the solid state have led to recent advances with silicon qubits. Researchers at University of California, Los Angeles and Princeton University, in collaboration with industry, demonstrated high-fidelity quantum logic operations with two silicon qubits and control architecture shown in Figure 3.1. This work was supported by the Army Research Office (ARO), LPS, and NSF. Several research frontiers motivate further work in this rapidly developing technology, including the use of machine learning to support classical control systems, the use of isotopically purified Silicon-28, alternative material platforms, and principles of spin-spin interactions.[15,16] International cooperation is critical for maintaining the pace of discovery and development of this technology, as related R&D is being pioneered in the Netherlands and Australia, among other locations, in collaboration with U.S. funding agencies.[17,18]

[14] 'Two-qubit silicon quantum processor with operation fidelity exceeding 99%,' doi:10.1126/sciadv.abn5130; image reproduced with permission from doi:10.48550/arXiv.2111.11937

[15] 'Semiconductor spin qubits,' doi:10.1103/RevModPhys.95.025003

[16] 'Colloquium: Advances in automation of quantum dot devices control.' doi:10.1103/RevModPhys.95.011006

[17] 'Universal control of a six-qubit quantum processor in silicon,' doi:10.1038/s41586-022-05117-x

[18] 'Optimisation of electron spin qubits in electrically driven multi-donor quantum dots,' doi:10.1038/s41534-022-00646-9

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. Quantum effects set fundamental limits on measurement precision and therefore, by necessity, NIST has been a global leader in QIS R&D. The emerging U.S. quantum industry faces many technical challenges as it seeks to unlock the transformative potential of QIS. Scaling and connecting quantum systems, improving device performance and robustness, growing the talent pool to perform this work, and developing technical standards that enable businesses to succeed are some of the ways in which NIST is promoting innovation and industrial competitiveness in QIS. More broadly, NIST conducts open, world-class research touching upon all elements of the national QIS agenda, with an emphasis on precision metrology and cybersecurity.[19] NIST advances QIS through its core technical programs on quantum sensing, computing, networking, enabling technologies, risk mitigation, and foundational science, including at its joint institutes (JILA,[20] the Joint Quantum Institute (JQI),[21] and the Center for Quantum Information in Computer Science (QuICS)[22]). NIST established and supports an industry-led consortium (the Quantum Economic Development Consortium, or QED-C)[23] working to accelerate the growth of the U.S. quantum industry by identifying gaps in technology, supply chain, standards, workforce, and ways to address these gaps through collaboration. The NIST FY 2024 budget request includes support to "improve the metrology of high-fidelity, scaled quantum systems, across multiple and hybrid physical platforms, [and] supporting U.S. industry efforts…with an emphasis on practical quantum applications," to be conducted with industry, academic, and government partners.[24]

QIS R&D activities supported by NIST include:

- NIST continues to grow its foundational and applied QIS research programs on quantum-enhanced sensing and precision measurement, quantum networking and communications, quantum computing and simulation, fundamental physics, key enabling technologies, and applications of quantum technologies in chemistry, materials, biology, and healthcare.
- Over the past year, NIST has continued to develop its quantum networking program on both NIST campuses, begun a program on integrated photonics for quantum technologies, enhanced quantum characterization and benchmarking activities, continued to grow foundational QIS R&D activities, and expanded the atomic clock program to enable the deployment of state-of-the-art technologies for timekeeping applications. NIST has also emphasized the support of early-career researchers as part of an internal strategy for growing the NIST quantum workforce, in line with the national QIST Workforce Development Strategic Plan.
- NIST continues to engage with the U.S. quantum industry through cooperative research and development agreements (CRADAs) to address specific technology gaps, and more broadly with the QED-C, which now has participation from more than 170 companies involved in developing quantum technologies and their associated supply chains. In total, the QED-C has approximately 230 members. Internationally, the consortium has extended its membership model to include 38 countries, and it partners with other countries and regions' quantum

[19] https://www.nist.gov/topics/quantum-information-science
[20] https://jila.colorado.edu/
[21] https://jqi.umd.edu/
[22] https://quics.umd.edu/
[23] https://quantumconsortium.org/
[24] https://www.commerce.gov/sites/default/files/2023-03/NIST-NTIS-FY2024-Congressional-Budget-Submission.pdf

industry consortia. This year QED-C began an R&D program on control and readout electronics for quantum systems and held a workshop on integrated photonics for quantum applications.

- NIST performs workforce development activities through partnerships with higher-education institutions at its joint institutes, its Professional Research Experience Program (PREP), its Summer Undergraduate Research Fellowship (SURF) program, and through its National Research Council (NRC) Postdoctoral Fellowship program.
- NIST has continued its long history of QIS research collaboration with NSF, DOE, DOD, and the IC, including substantial and sustained sponsorship by partner agencies, especially at its joint institutes. NIST researchers contribute to many of the NSF and DOE quantum centers, notably Quantum Systems through Entangled Science and Engineering (Q-SEnSE), Quantum Systems Accelerator (QSA), Superconducting Quantum Materials and Systems Center (SQMS), and the Institute for Robust Quantum Simulation (RQS).
- The NIST PQC program is crucial to securing U.S. public key infrastructure once full-scale quantum computers are available. NIST has announced candidate PQC algorithms for standardization, as well as candidates for a fourth round of analysis. NIST released its draft Federal Information Processing Standards (FIPS) PQC standards for public comment in August 2023 and expects to publish these PQC standards in 2024.[25]
- NIST has state-of-the-art cleanroom facilities for the fabrication of QIS devices, including superconducting circuits, ion traps, nano-mechanical structures, integrated photonic circuits, and spin-qubit devices. NIST's Center for Nanoscale Science and Technology (CNST) in Gaithersburg is a national user facility which provides access to a comprehensive fabrication tool set, including advanced capabilities for lithography, thin-film deposition, and nanostructure characterization, as well as support from expert staff. NIST's Boulder Microfabrication Facility (BMF) provides state-of-the-art microfabrication and imaging capabilities to meet the needs of NIST researchers and their collaborators. The NIST on a Chip program heavily leverages these facilities to develop accurate measurement technologies.
- NIST works collaboratively with its peer National Metrology Institutes (NMIs) around the world on quantum metrology, including methods for the dissemination of the International System of Units, or SI. NIST has signed a Memorandum of Understanding (MOU) with the UK's National Physical Laboratory (NPL) on joint QIS research opportunities, and NIST also chairs the recently formed Technical Committee 25 – Quantum Measurement and Quantum Information of the International Measurement Confederation (IMEKO), providing a unique venue for NMIs to jointly advance quantum metrology.
- This year, NIST has engaged in discussions with international partners on potential QIS collaboration and cooperation, including with Australia, Brazil, the European Union, India, Japan, the Netherlands, New Zealand, Singapore, South Korea, and the UK. NIST has a Foreign Guest Researcher Program that offers researchers from around the world the opportunity to work collaboratively with NIST scientists.

NIST QIS R&D activities highlights:

- (October 20, 2022) A NIST research group at JILA provided the first demonstration of an entangled matter-wave interferometer that can sense accelerations with a precision that surpasses the standard quantum limit. Future quantum sensors such as these are expected to provide more precise navigation, improve measurements of fundamental constants, make

[25] https://www.nist.gov/news-events/news/2023/08/nist-standardize-encryption-algorithms-can-resist-attack-quantum-computers

precise gravitational measurements to better monitor and understand the earth dynamics, and contribute to fundamental physics, such as dark matter studies.[26]

- (November 10, 2022) NIST researchers achieved record accuracy of radio frequency signal synthesis — a critical step toward a broadband, integrated, quantum-based microwave voltage source with useful power.[27]

Box 3.2

Highlight: Greater Versatility for Quantum Computing with Superconducting Qubits

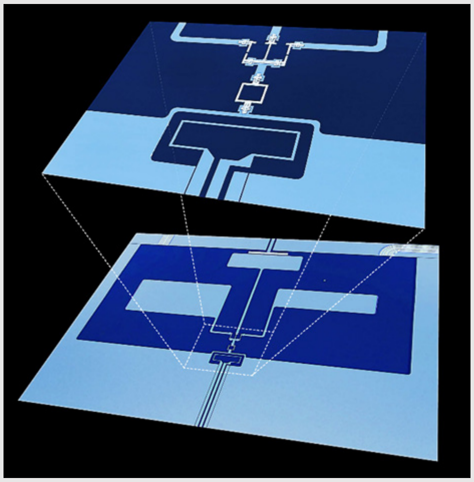

Figure 3.2: The central working region of a new superconducting quantum computing device. In the lower section, the three large rectangles (light blue) represent two qubits, at right and left, with a readout resonator in the center. In the upper, magnified section, a microwave antenna (large dark-blue rectangle at bottom) is used to induce a magnetic field in a SQUID loop (smaller white square at center), which activates the toggle switch. [28]

Researchers developed a software programmable "toggle switch" that enables superconducting qubits to be connected and disconnected from readout circuitry.[28] The switch can also be used to connect the qubits for quantum information processing or isolate qubits, which protects from noise during calculations, and when calculations are complete, results can be read out with high fidelity. The scheme provides architecture and algorithm designers with a new tool, and the parametric approach creates an extensible, tunable cavity quantum electrodynamic framework with various future applications, such as entanglement and error correction, state and entanglement stabilization, and parametric logical gates. Given that the switches are controlled by microwave pulses at a distance, a chip built with many of these switches could form the basis for a more easily programmable quantum computer, rather than those that rely on a fixed architecture.

Led by NIST, the team included researchers from academia and industry and was supported by NIST and DOE.[29]

- (November 17, 2022) NIST researchers developed and studied two-dimensional grids of quantum-dots with the potential for quantum simulation and computing. Multiple 3-by-3 grids

[26] https://www.nist.gov/news-events/news/2022/10/entangled-matter-wave-interferometer-now-double-spookiness
[27] https://www.nist.gov/news-events/news/2022/11/record-level-radio-frequency-signal-synthesis-quantum-based-accuracy
[28] https://www.nist.gov/news-events/news/2023/06/nist-toggle-switch-can-help-quantum-computers-cut-through-noise; image credit: K. Cicak and R. Simmonds
[29] https://www.nature.com/articles/s41567-023-02107-2

of precisely spaced phosphorus atoms were engineered, enabling a precise understanding and control of electron behavior in the structures.[30]

- (December 9, 2022) In four separate studies, NIST researchers and colleagues explored novel techniques to search for dark matter, such as experiments using superconducting nanowire single photon detectors (SNSPDs) and proposed theoretical studies for trapped electrons and space-based atomic clocks as quantum sensors.[31]
- (January 3, 2023) A NIST-led team of researchers demonstrated integrated photonics circuits for optical quantum information applications with quantum dots. The novel low-loss circuits are a hybrid of gallium arsenide semiconductor devices made at NIST and silicon nitride waveguides made at the University of California Santa Barbara.[32]
- (January 23, 2023) NIST researchers and colleagues at JQI and the NSF RQS QLCI used ultracold atoms to perform quantum simulation of space-time curvature which further explains the quantum hall effect and topological insulators.[33]
- (May 12, 2023) In an article entitled *Astronomy Tool Can Now Detect COVID in Breath*, NIST researchers at JILA explained how optical frequency combs can be used to perform fast, noninvasive tests for COVID-19 and potentially other diseases as well.[34]
- (June 25, 2023) In an article entitled *Laser-Comb Clocks Pierce Femtosecond Barrier*, NIST researchers explain how portable, ultraprecise timekeeping will usher in high-resolution GPS and gravity mapping.[35]
- (August 24, 2023) NIST released a Request for Comments on the initial public draft of three FIPS for PQC.[36] These proposed standards specify key establishment and digital signature schemes that are designed to resist future attacks by quantum computers, which threaten the security of current standards. The three algorithms specified in these standards are each derived from different submissions to the NIST PQC Standardization Project.
- (September 7, 2023) NIST released its *Single-Photon Sources and Detectors Dictionary*.[37] The report was written with the goal of promoting a better understanding and communication of terms common to the quantum and single-photon communities. The resulting language also allows commercial devices to be compared directly and helps clarify to users what performance they can expect.

[30] https://www.nist.gov/news-events/news/2022/11/nists-grid-quantum-islands-could-reveal-secrets-powerful-technologies
[31] https://www.nist.gov/news-events/news/2022/12/unveiling-universe-4-new-studies-nist-explores-novel-ways-hunt-dark-matter
[32] https://www.nist.gov/news-events/news/2023/01/chip-circuit-light-could-be-applied-quantum-computations
[33] https://jqi.umd.edu/news/twisting-atoms-through-space-and-time
[34] https://www.scientificamerican.com/article/astronomy-tool-can-now-detect-covid-in-breath/
[35] https://spectrum.ieee.org/atomic-clock-femtosecond-accuracy
[36] https://www.federalregister.gov/documents/2023/08/24/2023-18197/request-for-comments-on-draft-fips-203-draft-fips-204-and-draft-fips-205
[37] https://www.nist.gov/news-events/news/2023/09/unity-photon-community

3.2 The National Science Foundation (NSF)

NSF promotes the progress of science by funding research at over 2000 academic institutions throughout the United States, in a broad range of scientific and engineering disciplines.[38] The NQI Act calls on NSF to support multidisciplinary centers for QIS research and education, and coordinate core programs relevant to the field. Implementation of these activities is ongoing with a broad range of efforts highlighted at nsf.gov/quantum.[39] NSF's FY 2024 budget request to Congress articulates two goals for investments in QIS: (1) "pioneer development of quantum computing, communication, sensing, and networking to advance information processing, transmission, and measurement in ways that classical approaches can only do much less efficiently, or not at all;" and (2) "develop proof-of-concept devices, tools, systems, and applications with a demonstrable quantum advantage over their classical counterparts."[40]

QIS R&D Programs at NSF:

- **Quantum Leap Challenge Institutes** (QLCIs) are large multidisciplinary centers for QIS and engineering research and education, created in alignment with the NQI Act.[41] Five QLCI sites were established during 2020 and 2021. They currently foster partnerships with 89 academic institutions and 67 commercial firms. They engage over 180 faculty, 110 Postdocs, and 400 students, and have produced over 280 peer-reviewed research publications.
- **Expanding Capacity in Quantum Information Science and Engineering** (ExpandQISE) Solicitations NSF 23-551 and 22-561 serve to increase research capacity and broaden participation of institutions across the United States engaged in QIS and quantum engineering by providing support to build and maintain close connections between new efforts and already-impactful QIS centers or research institutions. Establishing and nurturing a critical mass of QIS talent at more institutions is an intentional goal. The ExpandQISE program now funds a total of 33 projects with a budget of $62.4 million, including eight awards to Historically Black Colleges and Universities (HBCUs), eight awards to institutions in Established Program to Stimulate Competitive Research (EPSCoR) jurisdictions, six awards to Hispanic Serving Institutions, and 28 awards to non-R1 institutions.[42]
- **Transformational Advances in Quantum Systems** (TAQS) programs support teams of three or more investigators with collaborative, interdisciplinary projects that apply QIS engineering concepts. TAQS solicitations may have a different S&T focus each year with the most recent on Quantum Sensing Challenges (NSF 22-630), which focused on opportunities to enhance sensors by applying QIS considerations.[43]
- **The National Quantum Virtual Laboratory** (NQVL) program (NSF 23-604) will foster a community-wide effort to facilitate the translation of basic science and engineering to the resultant technology, while emphasizing and advancing the scientific and technical value of this technology. Following a co-design concept, the NQVL will catalyze the development of use-inspired quantum technologies by integrating end-users and potential customers from multiple fields of science, engineering, and other sectors of the economy into cycles of research, development, and demonstration. It is designed to lower barriers for quantum technology users to pioneer and accelerate the realization of new applications.

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[38] https://nsf.gov/news/factsheets/Factsheet_By%20the%20Numbers_05_21_V02.pdf
[39] https://www.nsf.gov/quantum
[40] https://nsf-gov-resources.nsf.gov/2023-03/01_fy2024.pdf
[41] https://beta.nsf.gov/funding/opportunities/quantum-leap-challenge-institutes-qlci
[42] https://www.quantum.gov/nsf-invests-an-additional-38m-to-expand-participation-in-qise/
[43] https://new.nsf.gov/news/quantum-scale-sensors-yield-human-scale-benefits

- **Core programs** are the primary source of support from NSF to QIS and quantum engineering in a wide variety of disciplines, including computer science, engineering, biology, and mathematical and physical sciences. Mainly via core programs, NSF is currently funding approximately 1,500 projects at more than 260 institutions in 48 states led by over 2000 investigators, and training over 4000 graduate students. [44] The "Connections in QIS" webpage lists several core programs underpinning QIS research. [45] These core programs are recognized as an important source of new ideas and also serve as a gateway for including individuals and institutions that are not currently engaged in QIS research, especially those at Minority Serving Institutions (MSIs) and emerging research institutions.
- **Other large-scale QIS and quantum engineering 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 Institute for Quantum Information and Matter (IQIM) at the California Institute of Technology, the Massachusetts Institute of Technology-Harvard Center for Ultracold Atoms (CUA), the JILA Physics Frontier Center at the University of Colorado, the multi-institutional Software-Tailored Architecture for Quantum co-design (STAQ) project led by Duke University, the multi-campus research and education cluster on Emergent Quantum Materials and Technologies (EQUATE) led by the University of Nebraska, the Enabling Practical-Scale Quantum Computation (EPiQC) Expeditions in Computing project led by the University of Chicago, and several Materials Research Science and Engineering Center (MRSEC) projects focused on quantum technologies such as the Princeton Center for Complex Materials, [46] the Columbia Center for Precision-Assembled Quantum Materials (PAQM), the Ohio State University Center for Emergent Materials, the Chicago Materials Research Center, the University of Illinois MRSEC, the University of Washington Molecular Engineering Materials Center, the University of Texas Center for Dynamics and Control of Materials, the University of Tennessee Knoxville Center for Advanced Materials & Manufacturing (CAMM), and the Center for Materials Innovations at Michigan. The National Nanotechnology Coordinated Infrastructure (NNCI) program, and several Centers for Chemical Innovation (CCI) program sites such as the Center for Quantum Dynamics on Modular Quantum Devices and the Center for Quantum Electrodynamics for Selective Transformations also contribute to portfolio.

NSF QIS R&D activities highlights:

- (July 21, 2022) NSF released a Dear Colleague Letter (NSF 22-108) on International Collaboration Supplements in QIS, inviting requests for supplemental funding from existing research awardees to add a new — or strengthen an existing — international dimension to their QIS and engineering research.[47]
- (August 1-3, 2022) NSF hosted a workshop on Quantum Advantage and Next Steps at the University of Chicago. This workshop brought together quantum computing theorists and experimentalists to discuss the state-of-the-art research on quantum advantage.

[44] Statistics are based on information provided by Principal Investigators in annual reports to NSF on QIS-related projects.
[45] https://beta.nsf.gov/funding/opportunities/connections-quantum-information-science-cqis
[46] https://new.nsf.gov/news/nsf-invests-162-million-research-centers
[47] https://www.nsf.gov/pubs/2022/nsf22108/nsf22108.jsp

Box 3.3

Highlight: Erasure Qubits and Mid-Circuit Measurements

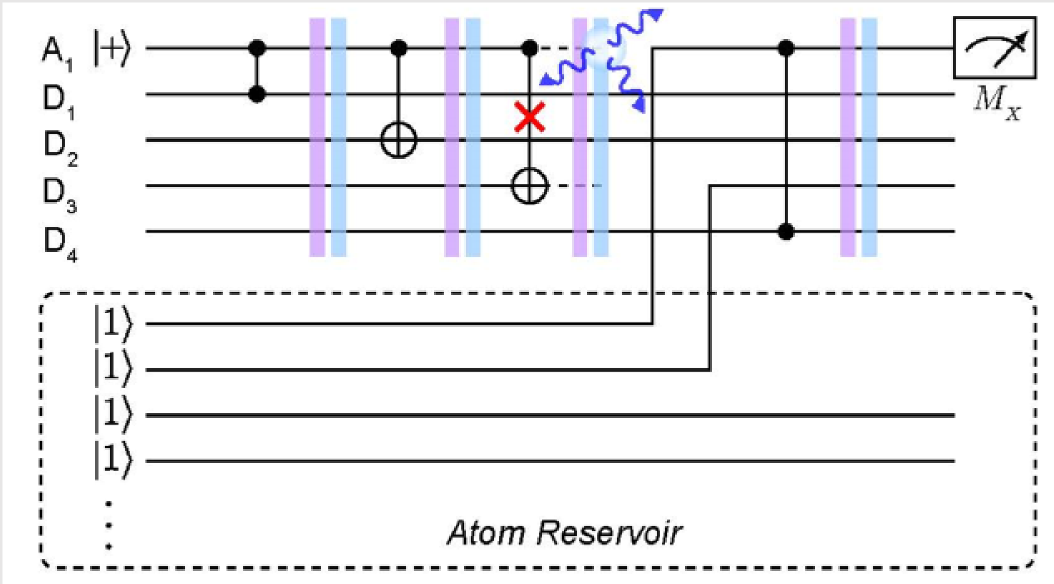

Figure 3.3: Schematic quantum circuit with programmed replacement of qubits with erasure errors, based on mid-circuit measurements, capable of detecting leakage from the computational subspace. [48]

A possible path towards fault-tolerant quantum computing is the use of "erasure qubits" to herald errors with mid-circuit measurements and correct for errors in quantum logic operations. An instance proposed and demonstrated by researchers at Princeton University and Yale University leverages the level structure of ytterbium-171 atoms to convert the dominant source of error for two qubit gates — spontaneous decay from the Rydberg state — into detected erasures.[48,49] Replacing erased qubits with freshly prepared atoms from a reservoir, as shown in Figure 3.3, enables a substantial (greater than four-fold) increase in the threshold for two-qubit errors that can be tolerated while implementing quantum error correction.[48] Related experiments and demonstrations were performed at Berkeley, Harvard University, the California Institute of Technology, and industry.[50–53] Implementation with trapped ions is being explored at the University of California Los Angles and Duke University.[54] Erasure qubits are also being explored with superconducting qubit platforms.[55,56,57] Application of mid-circuit measurements and erasure qubits is bringing the threshold to within the range of current experimental gate fidelities, advancing the frontier of fault tolerant quantum computing.

[48] 'Erasure conversion for fault-tolerant quantum computing in alkaline earth Rydberg atom arrays,' doi:10.1038/s41467-022-32094-6; figure reproduced with permission doi:10.48550/arXiv.2201.03540
[49] 'High-fidelity gates and mid-circuit erasure conversion in an atomic qubit,' doi:10.1038/s41586-023-06438-1
[50] 'Mid-circuit cavity measurement in a neutral atom array,' 10.1103/PhysRevLett.129.203602
[51] 'Hardware-efficient, fault-tolerant quantum computation with Rydberg atoms,' 10.1103/PhysRevX.12.021049
[52] 'High-fidelity parallel entangling gates on a neutral atom quantum computer,' doi:10.1038/s41586-023-06481-y
[53] 'Erasure conversion in a high-fidelity Rydberg quantum simulator,' doi:10.1038/s41586-023-06516-4
[54] 'Quantum error correction with metastable states of trapped ions using erasure conversion,' doi:10.1103/PRXQuantum.4.020358
[55] 'Erasure qubits: Overcoming the T_1 limit in superconducting circuits,' doi:10.48550/arXiv.2208.05461
[56] 'Demonstrating a superconducting dual-rail cavity qubit with erasure-detected logical measurements,' doi:10.48550/arXiv.2307.03169
[57] 'Demonstrating a long-coherence dual-rail erasure qubit using tunable transmons,' doi:10.48550/arXiv.2307.08737

- (September 23, 2022) NSF announced a new solicitation for the Quantum Sensing Challenges for TAQS (QuSeC-TAQS) program. The program supports interdisciplinary teams of three or more investigators to explore highly innovative, original, and potentially transformative research on quantum sensing. In August 2023, NSF announced $29 million in QuSeC program awards, to advance applications of quantum sensing in a range of fields including astronomy, biology, geodesy, chemistry, materials science, and physics.[58]
- (October 28, 2022) NSF hosted a virtual workshop on Software-Hardware Co-Design for Quantum Computing, which functioned as a hub to spur a large, synergistic, and convergent effort for building a common technological ecosystem so that quantum-enabled and classical technologies can co-exist for mutual benefit and progress in the long term.
- (February 3, 2023) The ExpandQISE solicitation was revised for 2023 and included collaboration with DOE. The solicitation aims to increase research capacity and broaden participation in QIS and quantum engineering. With grants up to $5 million over up to five years, depending on the track, the program will expand quantum engagement to new institutions. In September 2022, NSF announced $21.4 million in awards for the ExpandQISE program in round one,[59] and in August 2023, NSF announced $37.5 million in awards for the ExpandQISE program for round two.[60]
- (March 19-24, 2023) An NSF Research Coordination Network award brought together scientists from multiple nations on a weekly basis and their efforts resulted in the development of the Quantum Biology topic as one of the areas of the Gordon Research Conferences. The inaugural conference was held on March 19-24, 2023 in Galveston, Texas.
- (March 23-24, 2023) The NSF EPSCoR Program hosted a Workshop on Quantum Computing and QIS and Engineering at NSF Headquarters in Alexandria, VA. This workshop brought together researchers and administrators from the EPSCoR states and territories to identify how their institutions can better contribute to the field of QIS.[61]
- (May 3, 2023) NSF issued a Request for Information (RFI) to gather insights for the development of an investment roadmap for its Directorate for Technology, Innovation, and Partnerships (TIP), which was authorized by the CHIPS and Science Act. This roadmap will guide investment decisions in use-inspired and translational research over a three-year timeframe to advance U.S. competitiveness and develop the U.S. workforce in 10 critical technology areas, including QIS.[62]
- (June 26, 2023) NSF announced new awards for MRSECs, several of which address quantum control of materials and materials for quantum information processing.[63]
- (July 17, 2023) NSF issued the solicitation (NSF 23-604) for the first phase of the NQVL.[64]

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[58] https://new.nsf.gov/news/quantum-scale-sensors-yield-human-scale-benefits
[59] https://new.nsf.gov/news/nsf-announces-increased-support-capacity-building
[60] https://new.nsf.gov/news/more-institutions-participate-quantum-science
[61] https://quantumcomputing.msstate.edu/wp-content/uploads/qCISE_report.pdf
[62] https://new.nsf.gov/tip/updates/nsf-seeks-input-develop-investment-roadmap
[63] https://new.nsf.gov/news/nsf-invests-162-million-research-centers
[64] ‘Accelerating progress towards practical quantum advantage: the quantum technology demonstration project roadmap,’ doi:10.48550/arXiv.2210.14757

3.3 The Department of Energy (DOE)

DOE ensures America's prosperity and security through a variety of efforts including basic and applied scientific research, discovery and development of new technologies, and isotope production. The DOE National Laboratories are a system of intellectual assets, unique among world scientific institutions, that also serve as regional engines of economic growth across the country.[65] As authorized by the NQI Act, DOE established five National QIS Research Centers, and it continues to strengthen and coordinate QIS research throughout its core programs. The DOE Office of Science's (SC's) QIS website provides detailed information about SC QIS programs and access to SC-sponsored workshop reports.[66]

QIS R&D Programs at DOE:

QIS activities span the technical breadth of DOE SC, with investments from all of its research programs — Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), Biological and Environmental Research (BER), Fusion Energy Sciences (FES), High Energy Physics (HEP), the Isotope Program (IP), and Nuclear Physics (NP). DOE SC supports a diverse portfolio of QIS research on quantum sensing, computing, and networking, as well as infrastructure and supporting technology. In addition, the DOE National Nuclear Security Administration conducts ongoing QIS research.

The DOE SC Program Office's QIS web pages,[67] previous years' Annual Reports on the NQI Program, and the DOE FY 2024 Budget Request contain a broad discussion of how QIS connects to the mission of each DOE component. In brief:

- Quantum sensing efforts in the core DOE SC research programs include biosensors and bioimaging instrumentation and applications, the 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 the 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 to 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 and infrastructure for QIS includes infrastructure development in DOE user facilities, such as the Nanoscale Science Research Centers, quantum computing and networking testbeds, foundries for spin and superconducting qubits, and the development and stewardship of technologies for producing isotopes needed for quantum systems.
- Community Resources: 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] User facilities that have strong engagement with the QIS research community include Leadership Computing, X-ray, Neutron, Nanoscale Science, and Fermilab Cryogenic Facilities. Additionally, Oak Ridge National Laboratory's (ORNL's) Quantum Computing User Program provides access to industrial quantum computing resources to a broad user base,[69] while DOE SC's Quantum

[65] https://science.osti.gov/Laboratories
[66] https://science.osti.gov/Initiatives/QIS
[67] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages
[68] https://science.osti.gov/User-Facilities
[69] https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

Computing Testbeds for Science program provides the research community with fully transparent access to novel quantum computing hardware at Sandia and Lawrence Berkeley National Laboratories.[70,71]

- Interdisciplinary Centers: The five DOE National QIS Research Centers leverage investments in research and facilities; create synergies with efforts developed by other agencies (e.g., NSF QLCIs, and the QED-C), the private sector, and academia; and bring unique approaches to community building. In addition, smaller research teams are supported as part of the Energy Frontier Research Centers, focusing on quantum materials and related QIS research.

DOE QIS R&D activity highlights:

Funding announcements:

- Since FY 2022, the DOE SC has accepted proposals for QIS through the Annual Open Solicitation that is available continuously throughout the FYs, as well as the annual solicitation for the SC Early Career Research Program. In addition, QIS is among the standing topics for the DOE SC small business innovation research (SBIR)/small business technology transfer (STTR) program.
- (August 8, 2022) As part of the DOE SC SBIR/STTR program, DOE ASCR announced its interest in receiving applications for software to facilitate the use of near-term quantum computing hardware, and DOE BER announced its interest in receiving applications for quantum enabled bioimaging and sensing approaches for bioenergy.[72]
- (September 13, 2022) DOE BER announced $18 million in awards for research in Bioimaging and Sensing Approaches for Bioenergy, which includes QIS-related projects such as prototype development of quantum-enabled light sources, microscope design, and quantum sensors of biomolecule function.[73]
- (September 19, 2022) DOE ASCR announced $15 million in awards for basic research to explore potentially high-impact approaches in scientific computing and extreme-scale science,[74] which includes QIS awards to address new approaches for developing quantum algorithms, universal models of quantum computing, and quantum computation on quantum sensor data.
- (December 14, 2022) DOE announced $4.6 million in awards for the ASCR New Energy Sciences Workforce (ASCR-RENEW) program, which seeks to increase participation of underrepresented groups in the quantum computing and networking workforce, and increase participation of underrepresented institutions in quantum computing and networking workforce training.[75]
- (December 14, 2022) DOE FES released a Funding Opportunity Announcement (FOA) on applications of QIS to Fusion Science and Technology, and Plasma Science and Technology, as well as QIS development that is enabled by FES-supported science. [76]
- (January 26, 2023) DOE NP announced $9.1 million in awards for advancing research on QIS and nuclear physics, from solving nuclear physics problems with quantum computers and the development of quantum sensors, to the R&D of next-generation superconducting materials and architectures for high coherence qubits.[77]

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[70] https://qscout.sandia.gov
[71] https://aqt.lbl.gov
[72] https://science.osti.gov/-/media/sbir/pdf/TechnicalTopics/FY23-Phase-I-Release-1-Combined-TopicsV308032022.pdf
[73] https://www.energy.gov/articles/doe-announces-178-million-advance-bioenergy-technology
[74] https://www.energy.gov/science/articles/department-energy-announces-15-million-exploratory-research-extreme-scale-science
[75] https://science.osti.gov/-/media/funding/pdf/Awards-Lists/FY22-ASCR-RENEW.pdf
[76] https://science.osti.gov/grants/FOAs/-/media/grants/pdf/foas/2023/SC_FOA_0002891.pdf
[77] https://www.energy.gov/science/articles/department-energy-announces-91-million-research-quantum-information-science-and

- (April 25, 2023) The DOE Grid Modernization Initiative announced a lab-only call to advance key R&D priorities needed to build a reliant, reliable, equitable, sustainable, and secure grid. Quantum facilities for computing, sensing, and security is one of five topics in the call.[78]
- (July 27, 2023) DOE ASCR announced $11.7 million in awards under the Quantum Testbed Pathfinder FOA, focusing on the fundamental physical limits of quantum processors, including how near-term quantum processors augment our understanding of the utility of quantum computers and how they will advance the frontiers of computational science.[79]
- (August 8, 2023) DOE announced $37 million in funding for 52 projects to 44 institutions to build research capacity, infrastructure, and expertise at institutions historically underrepresented in DOE SC's portfolio, such as MSIs and emerging research institutions (ERIs). Through the Funding for Accelerated, Inclusive Research (FAIR) initiative, DOE SC is supporting mutually beneficial relationships between MSIs/ERIs and partnering institutions to perform basic research across the SC portfolio. Six of the awards are related to QIS and quantum materials research.[80]
- (August 10, 2023) DOE ASCR announced $11 million in awards for 15 projects under the FOA on Exploratory Research for Extreme-Scale Science. Six of the projects focus on converting quantum algorithms from one model of quantum computing to another.[81]
- (August 24, 2023) DOE announced $70 million in funding to support research by historically underrepresented groups in STEM and to diversify leadership in the physical sciences. The funding, through DOE's Reaching a New Energy Sciences Workforce (RENEW) initiative, will support internships, training programs, and mentor opportunities at 65 different institutions, including 40 higher-learning institutions that serve minority populations. Of these, 14 institutions received awards to support research training opportunities in QIS, funded through the ASCR, BES, and HEP programs.[82]
- (August 29, 2023) DOE ASCR announced $24 million in awards for three collaborative projects in quantum networking research as part of the lab-only call for proposals on Scientific Enablers of Scalable Quantum Communications.[83]

R&D for Supporting Technology:

- DOE IP has developed new methods for producing stable isotopes of ytterbium-171, -172, and silicon-28, which are relevant to quantum memory and quantum computation, respectively. DOE IP is investigating a production pathway to replenish rubidium-87 inventories used in atomic clocks. Furthermore, DOE IP manages the helium-3 inventory for the nation and is working to develop new sources of helium-3, which is critical for the operation of cryogenics necessary for many QIS technologies.

Community Engagement, Workshops, and Reports:

- (July 13, 2022) DOE BER released a Transitioning Quantum Imaging and Sensing Technologies to Bioimaging Markets Research Study on QIST's potential to disrupt bioimaging.[84]
- (December 14, 2022) Q-NEXT (or the Next Quantum Science and Engineering) Center released A Roadmap for Quantum Interconnects that provides direction for related research across QIS

[78] https://www.energy.gov/gmi/2023-grid-modernization-lab-call
[79] https://www.energy.gov/science/articles/department-energy-announces-117-million-research-quantum-computing
[80] https://www.energy.gov/articles/us-department-energy-announces-37-million-build-research-capacity-historically
[81] https://www.energy.gov/science/articles/department-energy-announces-11-million-exploratory-research-extreme-scale-science
[82] https://www.energy.gov/articles/doe-announces-70-million-research-training-opportunities-students-and-faculty-historically
[83] https://www.energy.gov/science/articles/department-energy-announces-24-million-research-quantum-networks
[84] https://science.osti.gov/-/media/sbir/pdf/Market-Research/DOE_QuantumSenorTechToMarket-071422.pdf

and highlights key issues and research needed over the next decade for the worldwide QIS community.[85]

- (March 2023) DOE ASCR and NIH Office of Data Science Strategy held two roundtable discussions to identify biomedical-related computational and data science application areas that could benefit from quantum computing approaches, and to identify research and collaboration opportunities and challenges in the near-, medium-, and long-term.
- (July 11-13, 2023) DOE ASCR sponsored a Quantum Computing and Quantum Networking Basic Research Needs Workshop. The workshop identified priority research directions in quantum computing and networking to better position ASCR to realize the potential of quantum technologies in advancing DOE science applications.[86]

QIS R&D Advances:

- (September 23, 2022) ASCR supported research showed that classical machine learning algorithms can efficiently predict ground state properties and classify quantum phases of matter when trained from data generated from quantum experiments, boosting hopes that classical machine learning trained on experimental data can solve practical problems in chemistry and materials science.[87]
- (November 23, 2022) Q-NEXT-supported research demonstrated that the performance of a sensor network is limited by the inherent noise associated with the quantum states used to realize the network. The work described a novel approach to spatially distributed entanglement between network nodes that offers better scaling with network size than that of networks with only spatially-localized entanglement at each node.[88]
- (March 22, 2023) DOE SC NP funded research provided the first-ever experimental observation of entanglement between dissimilar particles — in this case, positive and negative pions. The work was conducted using the Solenoidal Tracker (STAR) detector at the Relativistic Heavy Ion Collider, a DOE SC user facility at Brookhaven National Laboratory.[89]
- (May 11, 2023) Co-design Center for Quantum Advantage (C^2QA) research identified different oxidation states of tantalum in superconducting processors and measured their distributions, which may elucidate the underlying microscopic sources of loss that limit coherence time. This work was enabled by the Center for Functional Nanomaterials and the National Synchrotron Light Source II DOE user facilities.[90]
- (June 20, 2023) DOE SC BES funded research developed a unique instrument to directly visualize a variety of light-induced exciton states that can form in monolayer transition metal dichalcogenides (TMDs). Experiments support some current theories of exciton coupling in TMDs, but they also shed light on important discrepancies. This work is a key step towards the harnessing potential of TMDs for nanotechnology and quantum sensing.[91]
- (August 21, 2023) DOE SC BER funded research showed that entanglement is strongly preserved in a two-photon absorption process with organic molecules, providing a new concept for the development of quantum light-based spectroscopy and microscopy.[92]

[85] https://publications.anl.gov/anlpubs/2022/12/179439.pdf
[86] https://www.orau.gov/ASCR-BRN-Quantum
[87] 'Provably efficient machine learning for quantum many-body problems,' doi:0.1126/science.abk3333
[88] 'Distributed quantum sensing with mode-entangled spin-squeezed atomic states,' doi:10.1038/s41586-022-05363-z
[89] https://www.energy.gov/science/np/articles/new-type-entanglement-lets-scientists-see-inside-nuclei
[90] 'Chemical profiles of the oxides on tantalum in state of the art superconducting circuits,' doi:10.1002/advs.202300921
[91] https://www.energy.gov/science/bes/articles/directly-imaging-quantum-states-two-dimensional-materials
[92] 'Colors of entangled two-photon absorption,' doi:10.1073/pnas.2307719120

Box 3.4

Highlight: Quantum Error Correction Moves Beyond Breakeven

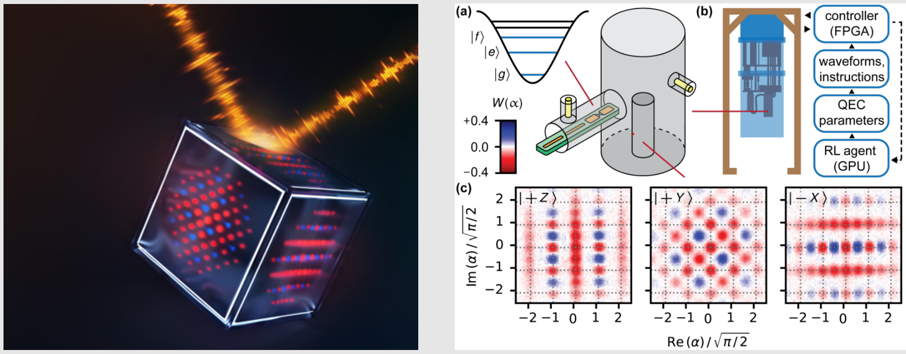

Figure 3.4: (Left) Representation of a logical qubit embedded into the state space of a harmonic oscillator using grid code, represented here by the faces of a cube.[93] Quantum error correction protects these grid states from corruption by a noisy environment, symbolized by the ray. (Right) Description the experimental system and quantum states involved in error correction.[94]

Decoherence is a fundamental phenomenon through which classical behavior emerges from the quantum laws of nature and is the main obstacle to leveraging quantum states for information processing. In practical terms for quantum computing, decoherence is caused by external factors, such as stray radiation, that can result in a quantum computer's qubits to change their quantum states and lose their stored information. Quantum error correction repairs the effects of decoherence on quantum information. However, in essentially all past experimental attempts to implement error correction, it was slower than the effect of decoherence. This meant a quantum system lost information faster than the corrections could keep up. Breakeven is the point where the added complexity of the correction circuit just barely makes up for the induced decoherence.

In this experiment, researchers extended the lifetime of quantum information past the breakeven point by more than twofold, confirming scientific expectations based on existing theory and establishing that there is no fundamental obstacle to extending the lifetime of quantum information through active intervention. It also opens the pathway towards quantum information processing in the presence of noise from radiation, cosmic rays, and other sources. Noise is an unavoidable nuisance for all real-world quantum systems. Looking forward, one of the next challenges is to realize high-fidelity logical operations between two error-corrected qubits on this platform.

This experiment realized the grid code in an electromagnetic mode residing in a superconducting cavity. The quantum state of this mode is controlled by an auxiliary superconducting circuit called the transmon. Scientists cooled this experimental system inside a dilution refrigerator to a temperature that is 100 times colder than the cosmic background of outer space. An external controller orchestrated the quantum error correction process with a latency of only a few hundred nanoseconds. A reinforcement learning agent optimized the process to counteract imperfections of the experimental setup and the controller.

This work was jointly funded by the DOE SC C^2QA and ARO.

[93] https://www.energy.gov/science/ascr/articles/quantum-error-correction-moves-beyond-breakeven; Image Credit: Polina Shmatkova
[94] 'Real-time quantum error correction beyond break-even,' doi:10.1038/s41586-023-05782-6; image reproduced with permission from doi:10.48550/arXiv.2211.09116

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 operational tests and evaluations of new technologies. Quantum science is one of DOD's 14 critical technology areas and has been a focus of sustained DOD funding for over 30 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 Air Force Research Laboratory (AFRL), the Air Force Office of Scientific Research (AFOSR), the Army Research Laboratory (ARL), ARO, the Naval Research Laboratory (NRL), and the Office of Naval Research (ONR). The DOD FY 2024 Budget Request highlighted that "quantum technology is approaching a tipping point that will determine how quickly it can make an impact. If the United States can stay on pace, many important outcomes for the DOD can be realized," with the intent to mature, accelerate, demonstrate, and transition emerging quantum technologies, along with their supporting supply chains.

DOD QIS R&D Programs:

The DOD quantum R&D programs span atomic clocks, quantum sensing, quantum computing, and quantum networking, from fundamental to applied R&D:

- Atomic clock programs across DOD are advancing the technology readiness level (TRL) of precision timekeeping technologies that support DOD missions such as synchronized timing and precision targeting, positioning, and navigation in denied environments. These efforts include: ONR's Next Generation Atomic Clock (NGAC) program,[95] ARL's Low-Cost Chip-Scale Atomic Clock (LC CSAC) program,[96] the United States Naval Observatory (USNO) timekeeping research for the USNO Master Clock, AFRL's Quantum Sensing and Timing Program, DARPA's H6 program,[97] and DARPA's Robust Optical Clock Network (ROCkN) program.[98]
- Quantum Sensors will address long-term military challenges for obtaining military advantage in intelligence, surveillance, and reconnaissance (ISR), as well as precision navigation and timekeeping (PNT). R&D programs to develop gyroscopes, accelerometers, magnetometers, gravimeters, and electrometers include the OUSD(R&E)/ARL Center for Excellence in Advanced Quantum Sensing,[99] DARPA's Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT),[100] Atomic-Photonic Integration (A-PhI),[101] Macaroni,[102] Science of Atomic Vapors for New Technologies (SAVaNT),[103] Quantum Apertures,[104] and Quantum Imaging of Vector Electromagnetic Radiation (QuIVER) programs,[105] the Army's Metrology program, ARL's Electromagnetic Field Sensing with Rydberg Atoms program,[106] ARO's Quantum State Engineering for Enhanced Metrology and Multi-qubit Enhanced Sensing and Metrology

[95] https://www.onr.navy.mil/-/media/Files/Funding-Announcements/Special-Notice/2020/N00014-20-S-SN17.ashx
[96] https://www.arl.army.mil/lccsac/
[97] https://www.darpa.mil/program/h6
[98] https://www.darpa.mil/program/robust-optical-clock-network
[99] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/
[100] https://www.darpa.mil/program/atomic-magnetometer-for-biological-imaging-in-earths-native-terrain
[101] https://www.darpa.mil/program/atomic-photonic-integration
[102] https://www.darpa.mil/program/macaroni
[103] https://www.darpa.mil/program/science-of-atomic-vapors-for-new-technologies
[104] https://www.darpa.mil/program/quantum-apertures
[105] https://www.darpa.mil/program/quantum-imaging-of-vector-electromagnetic-radiation
[106] https://www.army.mil/article/242980/army_researchers_detect_broadest_frequencies_ever_with_novel_quantum_receiver

Multidisciplinary University Research Initiatives (MURIs),[107] ONR's atom interferometry efforts for inertial and gravity sensors, the AFRL Strategic Atomic Navigation Devices and Systems (SANDS) program,[108] and the AFOSR MURI on Cold Molecules.

- Quantum Computing will address long-term military challenges in areas such as access to high-performance computing and secure cryptographic solutions. Ongoing basic research efforts include DARPA programs on Optimization with NISQ devices (ONISQ),[109] Quantifying the Utility of Quantum Computers (Quantum Benchmarking), and Underexplored Systems for Utility-Scale Quantum Computing (US2QC) programs,[110] the AFOSR MURIs on Quantum Programming Languages, Dissipation Engineering, and Quantum Random Access Memory, the ARO MURI on Enhanced Quantum Control via Spectator Qubits, and the ARO/AFOSR MURI on Modular Quantum Computing.
- Quantum Networks are expected to be a resource for fundamental R&D and impact the internal architectures for large-scale quantum systems such as quantum computers. The DOD service labs (AFRL, ARL, and NRL) have efforts in heterogenous quantum networking R&D including photonic, atom/ionic, and superconducting technologies, as well as efforts in algorithms, transduction, and joint ion-photonics designs of integrated photonic components. In addition, DOD quantum networking testbeds include the AFRL Distributed Quantum Information Test Bed and service-lab participation in the Washington Metropolitan Quantum Network Research Consortium (DC-QNet). Quantum networking programs include DARPA Quantum Augmented Network (QuANET) program,[111] ARO MURIs on Quantum Network Science and Entanglement and AFOSR MURIs on Quantum Many-Body Physics with Photons and Quantum Information Concepts from Tensor Networks.

DOD QIS R&D activity highlights:

Funding QIS R&D:

- (December 5, 2022) DARPA Defense Sciences Office issued an Advanced Research Concept opportunity for Imagining Practical Applications for a Quantum Tomorrow (IMPAQT), inviting submissions of abstracts for innovative exploratory research concepts in the technical domain of quantum computing applications.[112]
- (February 16, 2023) AFOSR has released two FOAs related to STEM education and instrumentation which could be leveraged by the quantum community.[113,114]
- (May 8, 2023) DARPA released a BAA for its QuANET program, which seeks to develop quantum-augmented networks that add novel security and covertness properties inherent in quantum communications to classical, non-quantum network infrastructures. QuANET will develop the hardware, protocols, and software tools required for missions and critical infrastructure, enabling the first viable transition strategy to operationalize quantum communications.[115]
- (June 3, 2023) DARPA is sponsoring an information session webcast for potential proposers on the objectives of the Synthetic Quantum Nanostructures (SynQuaNon) Disruption Opportunity,

[107] https://www.cto.mil/wp-content/uploads/2020/02/fy2020-muri-press-release.pdf
[108] https://afresearchlab.com/technology/quantum/
[109] https://www.darpa.mil/news-events/2020-05-11a
[110] https://www.darpa.mil/news-events/2021-04-02
[111] https://sam.gov/opp/4587b8304a0b4ad3828cb1bed1ee7482/view
[112] https://sam.gov/opp/eed111e0d59e459b87c9614ae3146e48/view
[113] https://www.grants.gov/web/grants/view-opportunity.html?oppId=345510
[114] https://www.grants.gov/web/grants/view-opportunity.html?oppId=345430
[115] https://sam.gov/opp/60917f7ea74845bf8f6aaa1382813f86/view

which is inviting submissions of innovative basic or applied research concepts in the domain of novel electronic metamaterials and nanostructures for applications to quantum-limited superconducting nanoelectronics.

- The Navy has established two new efforts: NRL launched the Quantum Science Institute to fund cutting edge R&D across QIS and its enabling technologies, and the Naval Information Warfare Center (NIWC) launched a five-year QIS program that focuses on basic research and workforce development.

QIS R&D in the News:

- (December 2, 2022) DOD issued a Request for Solutions for the Microelectronics Commons, a CHIPS and Science Act-funded national network to onshore microelectronics hardware prototyping, lab-to-fab transition of semiconductor technologies, and semiconductor workforce training. In particular, prototyping capabilities for six technology areas, which include quantum technologies, will be supported with seed projects in order to partially offset facility operating costs and to give these facilities experience in supporting outside users. For quantum technologies, the desired end-state is commercial foundry-like access with rapid turn-around times.[116] On September 20, 2023, DOD announced the award of nearly $240 million to eight Microelectronics Commons regional innovation hubs.[117]
- (January 10, 2023) NRL and all 14 Naval Warfare Centers signed an MOU with AFRL to establish a conduit for exchanging technical expertise and explore co-projects focused on creating useful quantum computing capabilities relevant to DOD. The agreement gives Navy scientists and engineers access to industrial quantum computing systems, through the AFRL hub, providing the ability to explore Navy-relevant problem sets.[118]
- (January 21, 2023) DARPA selected three industry performers for the US2QC program. In the first of four phases of US2QC, these companies will each present a design concept describing their plans to create a utility-scale quantum computer.[119]
- (April 3, 2023) Researchers from NIST, University of Maryland, and industry collaborated under the DARPA A-PhI program to successfully trap and arrange atoms in a chip-scale atomic optical lattice clock. Performers cooled atoms to microkelvin temperatures by developing ultra-stable laser technologies into small, low-power, chip-scale packages which are approximately 1,000 times smaller than a traditional, laboratory-scale optical-clock. This work is a critical step in moving from today's complicated, hand-assembled, free-space optics to integrated photonics. It also paves the way for advanced quantum sensors, advanced computing architectures, and high-capacity, secured data links.[120,121]

[116] https://nstxl.org/opportunity/microelectronics-me-commons/
[117] https://www.defense.gov/News/News-Stories/Article/Article/3532338/dod-names-8-locations-to-serve-as-new-microelectronics-commons-hubs/
[118] https://www.nrl.navy.mil/Media/News/Article/3263682/new-quantum-capabilities-for-naval-warfare-centers
[119] https://www.darpa.mil/news-events/2023-01-31a
[120] 'Integrating planar photonics for multi-beam generation and atomic clock packaging on chip,' doi:10.1038/s41377-023-01081-x
[121] https://www.nist.gov/programs-projects/compact-strontium-optical-clock-integrated-photonics

Box 3.5

Highlight: Quantum Sensors Tested at Rim of the Pacific Exercises

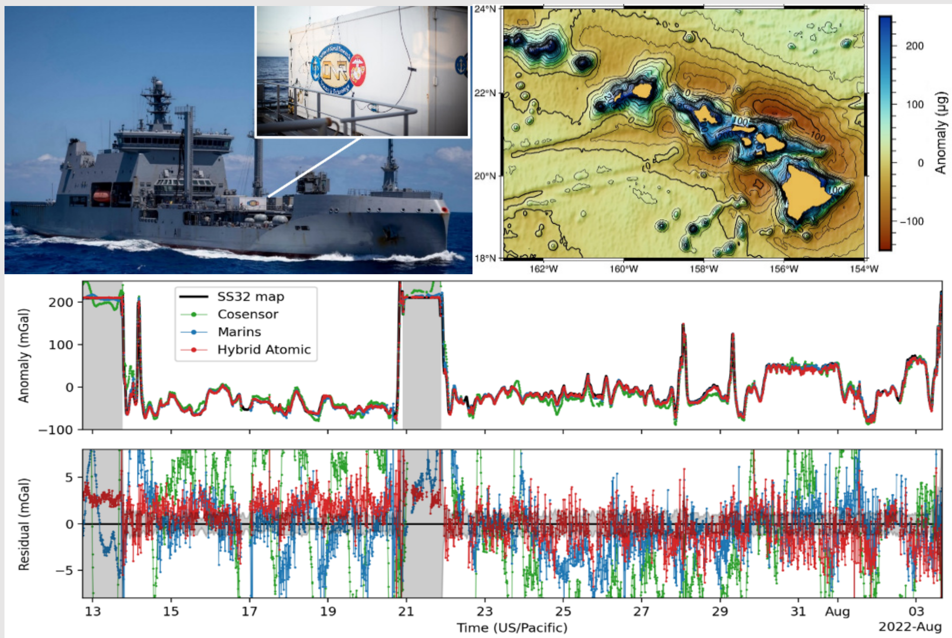

Figure 3.5: (Top left) The HMNZS Aotearoa underway at RIMPAC with an ONR shipping container used to support the various experiments is visible on the deck.[122] *(Top Right) Gravity map around Hawaii used for gravity map matching. (Bottom) Measurements of the RIMPAC data showing micro-g deviation of the atomic gravimeter verses other gravity anomaly map.*[123]

ONR collaborated with AFRL and the Five Eyes partners under The Technical Cooperation Program (TTCP) to test and demonstrate quantum sensors, quantum clocks, and related critical components aboard a New Zealand naval vessel at sea as a part of the US-hosted, multi-nation Rim of the Pacific (RIMPAC) 2022 exercises. It has been widely recognized in DOD and broader national and international communities that quantum sensors and clocks open extensive opportunities for non-GPS-based PNT and Intelligence, Surveillance, and Reconnaissance.

The ONR funded atomic sensor system, developed with Applied Research Laboratory at Pennsylvania State University and industry, coupled a classical inertial navigation system with an atom-interferometer-based accelerometer.[124] Gravity measurements were compared to a map of micro-g-scale deviation in the Earth's gravity field and processed into a position fix. The atomic system improved accelerometer bias and scale-factor and produced better performance than high-end, existing accelerometer technologies. Excellent performance and availability were observed at-sea for 21 days onboard HMNZS Aotearoa. The robustness of the atomic system, long lifetime, and operation under relevant dynamics showed promising signs of the advancing technology readiness level of the sensor. Ultimately DOD and ONR's goal is to integrate quantum inertial sensors into deployable naval systems.

The DOD partners leveraged TTCP nations to test and compare additional variations of optical atomic clock technology to help elucidate relative performance and military applicability. In general, the devices tested performed well, demonstrating exceptional stability and robust operation.

[122] Top Left Image Credit: Petty Officer 3rd Class Taylor Bacon.
[123] Top Right and Bottom Image Credit: Vector Atomic.
[124] 'Optical clocks at sea,' doi:10.48550/arXiv.2308.12457

- (June 14, 2023) The Secretary of the Army Christine E. Wormuth designated ARL as the Army QIS Research Center, as authorized by the NDAA for FY 2020. ARL joins AFRL and NRL as the third DOD QIS research center.
- (June 27-29, 2023) The fifth annual Quantum for International workshop was cohosted by AFRL, AFOSR, the Griffiss Institute, and the Innovare Advancement Center. This event is part of a global connectivity initiative to build an open ecosystem of government, academic, and industry collaborations and shape the future of quantum innovation for the United States and its partners.
- (August 8, 2023) AFRL launched the Extreme Computing facility, which comprises of state-of-the-art laboratories for trusted computing, machine learning, neuromorphic and nanocomputing, and quantum networking, which will advance our competitive edge in high-performance computing.
- Delaware State University is a Center for Excellence in Advanced Quantum Sensing supported by OUSD(R&E) and managed by ARL. This program provides a foundation to enhance participation among HBCUs and MSIs in DOD R&D.[125]

[125] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/

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 QIS research portfolio includes several activities led by various directorates and programs at NASA Headquarters (HQ), supported by the Jet Propulsion Laboratory (JPL), Glenn Research Center (GRC), Ames Research Center (ARC), and Goddard Space Flight Center (GSFC), along with national and international partners in academia and industry. These activities in basic- and applied-science and engineering span QIS areas in quantum computing, quantum sensing, quantum communications and networking, as well as space-based fundamental science and exploration.

NASA QIS R&D activity highlights

- NASA has efforts to develop gravity gradiometers to study climate change. NASA GSFC built a terrestrial testbed to develop an ultra-sensitive cold-atom gravity gradiometer with applications to mapping Earth's mass change, enabling new understanding of climate change processes and water and natural resource distribution. NASA's Space Technology Mission Directorate (STMD) made an award to the Quantum Pathways Institute, a consortium comprised of the University of Texas at Austin, the University of Colorado Boulder, and the University of California Santa Barbara, to focus on the development of quantum gravity gradiometry technologies to measure global climate change, including ice mass loss and ocean heat uptake.
- NASA GSFC is engaged in cross-government quantum networking research and experiments with seven agencies as a member of the DC-QNet consortium. NASA supported research topics spanning quantum-augmented network model adaptations, free-space quantum networking studies, and link-modeling for fiber stabilization.
- NASA's STMD made an Innovative Advanced Concepts Study award to JPL for using a next-generation dynamically tunable quantum radar technology to improve remote sensing studies of Earth and other worlds. This work utilizes reflected ground signals from other orbiting spacecraft to eliminate the need for large antenna deployments.
- In collaboration with an MIT Lincoln Laboratories, NASA established specialized testbeds to advance free-space quantum signal processing. The testbeds will focus on simulating atmospheric turbulence and the required correction for adaptive-optics system performance, and testing photon arrival synchronization for free-space entanglement swapping.
- NASA HQ selected seven new QIST fundamental physics projects that are expected to be awarded in FY 2024, which include three new investigations for the ISS CAL facility, and four ground investigations across quantum sensing to identify new opportunities for space based optical clocks, atom interferometry, and quantum networks.
- NASA ARC Quantum Artificial Intelligence Laboratory (QuAIL) collaborated with University of Toronto under the DOE C^2QA to advance quantum computing techniques for simulating open quantum systems. These systems are significantly more challenging to simulate than those that are isolated, which already go beyond the capabilities of even the largest supercomputers.[126]
- NASA ARC QuAIL supported work to demonstrate that superconducting quantum processors have sufficient robustness to overcome additional forms of errors that result from increasing qubit numbers. Introducing more qubits increases the number of errors, so the density of

[126] 'Two-Unitary Decomposition Algorithm and Open Quantum System Simulation,' doi:10.22331/q-2023-05-15-1002

errors must be sufficiently low for logical performance to improve with increasing quantum error correcting code size.[127]

- (March 2023) NASA QuAIL became part of the government testing and evaluation team for the DARPA US2QC program. The QuAIL team has a long history of service to DARPA, including ongoing work as part of the government test and evaluation for the DARPA Quantum-Inspired Classical Computing and Quantum Benchmarking programs.

Box 3.6

Highlight: NASA's Performance-Enhanced Array for Counting Optical Quanta (PEACOQ) Detector

Figure 3.6: Close-up photograph of the PEACOQ detector which can detect photons at a rate of a gigahertz.[128]

Superconducting nanowire single-photon detectors (SNSPDs) are critical components of photonic-based quantum technologies due to high-detection efficiency and low timing jitter. NASA has funded a long development arc of SNSPDs, reporting high count rates through time-walks and jitter corrections and free space coupled SNSPDs.[129,130] The performance-enhanced array for counting optical quanta (PEACOQ) detector is a SNSPD developed at NASA JPL that comprises of a linear array of 32 niobium nitride superconducting nanowires and enables high-rate quantum communication,[131] which may increase the range and reliability of QIS networks. The NASA team has gone beyond the state of the art by combining these performance metrics into a single device, with a detection efficiency of 75%, timing jitter below 50 picoseconds, and a dark count rate of 158 hertz.

The development arc of this work was funded by NASA, JPL, DARPA, DOE, and academia.

[127] 'Suppressing quantum errors by scaling a surface code logical qubit,' doi:10.1038/s41586-022-05434-1

[128] https://www.nasa.gov/feature/jpl/nasa-s-quantum-detector-achieves-world-leading-milestone; Image Credit: NASA/JPL-Caltech

[129] 'Time-walk and jitter correction in SNSPDs at high count rates,' doi:10.1063/5.0129147

[130] 'Free-space coupled superconducting nanowire single-photon detector with low dark counts,' doi:10.1364/OPTICA.444108

[131] 'High-speed detection of 1550 nm single photons with superconducting nanowire detectors,' doi:10.1364/OPTICA.478960

3.6 The National Security Agency (NSA)

NSA's LPS supports QIS R&D including quantum computing, sensing, and communications, along with several enabling technologies. Based on the importance of QIS to national security, LPS has spearheaded efforts to support the NQI and contribute to the goals of the National QIS Strategy. LPS sponsors extramural quantum computing programs that fund domestic and international research projects at universities, laboratories, and commercial enterprises, both directly and in partnership with ARO and other agencies.[132] LPS also conducts internal research related to quantum computing and sensing at its University of Maryland, College Park facility. In 2020, the LQC was created to support the NQI Act as a QIS Research Center, enabling strong interactions with agencies, industry, and academia across the Nation. As part of the LQC, the Qubits for Computing Foundry (QCF) was initiated to fabricate state-of-the-art qubits for the broader research community. In addition, NSA, in its cybersecurity capacity, is charged with several key roles in defending National Security Systems from the risks posed by the adversarial acquisition of a cryptographically-relevant quantum computing capability.

NSA QIST R&D activity highlights:

- LPS's extramural quantum computing research programs include: Quantum Computing in the Solid State with Spin and Superconducting Systems (QC-5), Stable High Fidelity Trapped Ion Systems, Quantum Characterization of Intermediate-Scale Systems, and the New & Emerging Qubit Science & Technology.
- LPS and ARO partnered to launch the QC-5 program in May 2023.[5] The program focuses on superconducting and semiconducting qubits across four sub-topics: modular quantum gates, fast control and readout schemes, noise in solid-state spin and superconducting systems, and gates on advanced qubits with superior performance.
- LPS is collaborating with AFOSR on two new QIS funding opportunities:
    - The Materials Characterization and Quantum Performance program takes a "materials-first" approach to improving stability and reproducibility of state-of-the-art qubits, with focuses on solid-state qubits built from semiconductor and superconductor material systems for use in gate-based quantum computing. The goal is to characterize quantum materials to identify correlations between material properties and qubit performance.
    - AFOSR and LPS awarded three outstanding quantum-computing proposals for the Young Investigator Program in the first year of the collaboration.
- The QCF, in partnership with MIT Lincoln Laboratory and Industry, provided state-of-the-art superconducting and spin qubits to research groups that would not otherwise have access. The first foundry project to move to a full offering has the capacity to support over twenty research projects per year.[133]
- LQC inaugurated the "Super Semi Lab," a multi-PI research laboratory with multiple dilution refrigerators supporting QIS materials research, superconducting qubit research, and semiconductor qubit research.
- LPS's quantum sensing research program develops highly sensitive magnetometers based on defect centers in solid state materials and focuses on applying these sensors to a wide range of national security problems.

[132] http://www.lps.umd.edu/solid-state-quantum-physics/index.html
[133] https://www.qubitcollaboratory.org/qubits-for-computing-foundry-qcf-announcement/

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. Since its inception in 2008, IARPA has invested in quantum-computing research, represented most recently by the Logical Qubits (LogiQ) program (2016-2023) and the latest program, Entangled Logical Qubits (ELQ).[134,135]

IARPA QIS R&D activity highlights:

- (January 23, 2023) IARPA and ARO released a Broad Agency Announcement for the ELQ program, which will have teams operate and entangle error-corrected logical qubits in a modular architecture. ELQ is a four-year program scheduled to start in 2023. By the end of the program, each performer team will have applied logical entanglement to demonstrations of logical-state teleportation at high-success rates.

Box 3.7

Highlight: Logical Qubits

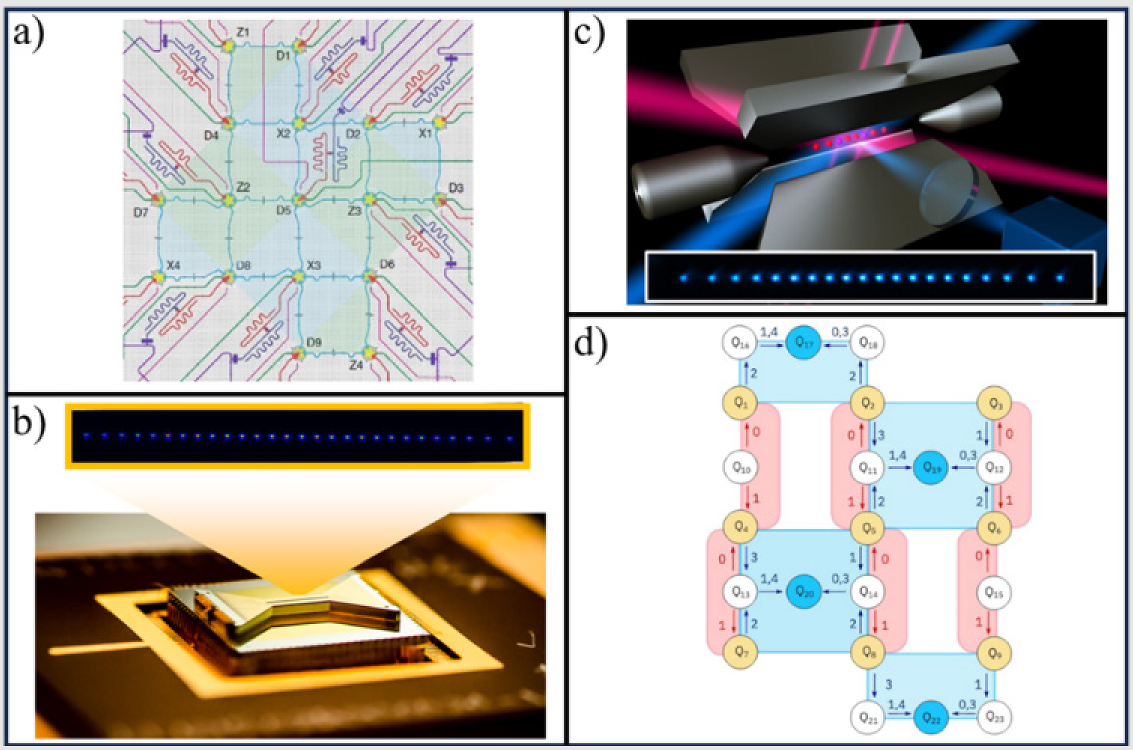

Figure 3.7: a) False-color image of the superconducting-qubit device realizing the surface-17 code;[136] b) an ion trap used to demonstrate a Bacon-Shor code (array of ytterbium ions inset);[137] c) illustration of the ion trap used to demonstrate the color code (array of calcium ions inset);[138] and d) mapping of heavy-hexagon code onto 23 transmon qubits.[139]

134 https://www.iarpa.gov/research-programs/logiq

135 https://www.iarpa.gov/research-programs/elq

136 'Realizing repeated quantum error correction in a distance-three surface code,' doi:10.1038/s41586-022-04566-8; image reproduced with permission from doi:10.48550/arXiv.2112.03708

137 'Fault-tolerant control of an error-corrected qubit,' doi:10.1038/s41586-021-03928-y; Image Credit: Duke University

138 'Demonstration of fault-tolerant universal quantum gate operations,' doi:10.1038/s41586-022-04721-1; Image Credit: University of Innsbruck

139 'Demonstrating multi-round subsystem quantum error correction using matching and maximum likelihood decoders,' doi:10.1038/s41467-023-38247-5; image reproduced with permission

Qubits inevitably tend toward error. To combat error, future large-scale, universal quantum computers will need to implement quantum error correction through structures known as logical qubits, each an organization of physical qubits that encodes quantum information redundantly, identifies errors, and receives repairs. The series of gates and measurements composing a logical qubit's functions must also abide by fault tolerance, a property conferred to operational sequences chosen so as not to propagate errors uncontrollably, for example, from one physical qubit to two, from two to four, and so on. In exchange for the added complexity, the use of logical qubits offers, ultimately, error suppression by orders of magnitude.

IARPA's now-concluded LogiQ program began in 2016 with the goal of bringing quantum error correction and fault tolerance from the theory and concepts of the time into scientific practice. What emerged, however, was much more. To begin, the program reached a major milestone in the demonstration of four logical qubits, each based on vastly different technologies and architectures which are presented in Figure 3.7. LogiQ also advanced manifold frontiers, in areas including quantum error correction theory, multi-qubit control hardware, multi-qubit device tune-up, and multi-qubit characterization and benchmarking. In addition to hundreds of publications, including both theoretical and experimental results, LogiQ researchers set future steps toward universal, fault-tolerant quantum computing on firm scientific ground.

- (May 2023) IARPA's LogiQ program concluded and demonstrated four different error-correcting logical qubits, one for each of its four distinct hardware platforms based on (1) flux-tunable transmon qubits, (2) trapped-ion hyperfine qubits, (3) trapped-ion optical-transition qubits, and (4) fixed-frequency transmon qubits. See Box 3.7 for a full LogiQ highlight.
- (May 18, 2023) Performers on the IARPA LogiQ program demonstrated up to ten rounds of fault-tolerant quantum error correction of a distance-three logical qubit on a superconducting qubit device.[140] Logical qubits are constructed from multiple physical qubits, which allow for error correction. Error correction can pose significant challenges to resources and control electronics, and this work combined the control of 23 qubits over deep circuits with decoding protocols that improved the survivability of logical states of up to 96.5% per round of quantum error correction.

Concluding Remarks for QIS R&D Overview

It should be emphasized that the selected QIS R&D highlights featured in the boxes and points throughout this Section provide only a small, but representative, sampling of the recent breakthroughs and capabilities that have been accelerated by NQI activities.

[140] 'Demonstrating multi-round subsystem quantum error correction using matching and maximum likelihood decoders,' doi:10.1038/s41467-023-38247-5

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.

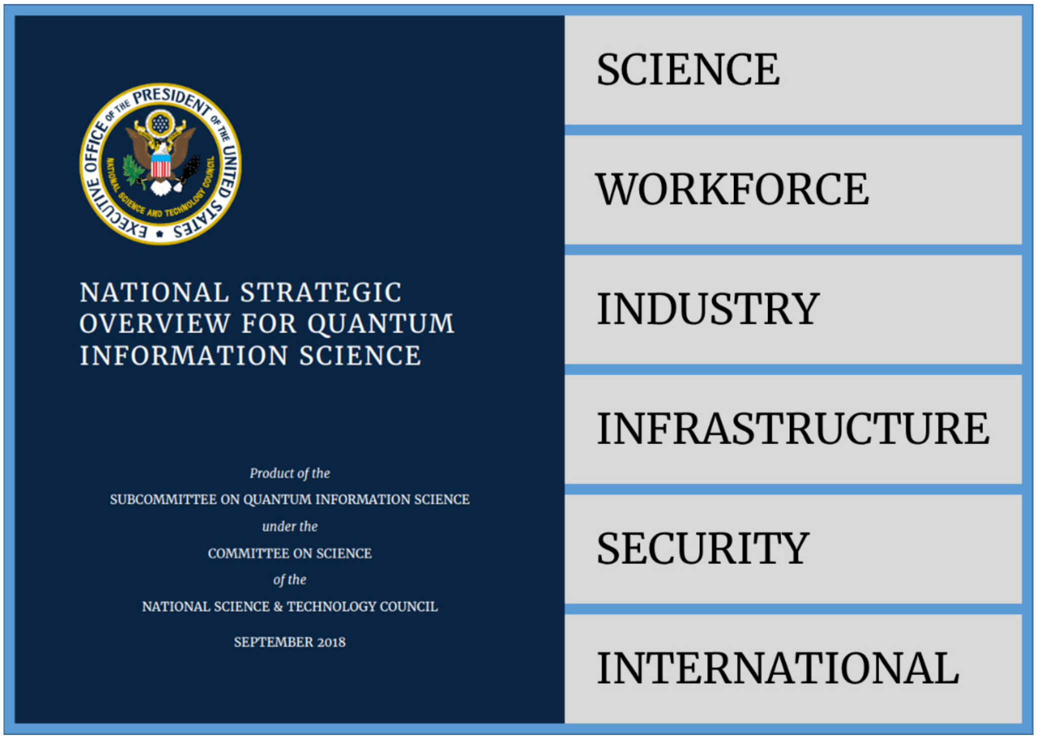

Figure 4.1: Policy topics discussed in the *National Strategic Overview for QIS*.

4.1 Choosing a Science-First Approach to QIS

Investment in fundamental science provides a foundation for the Nation's prosperity and security.[141] Historically, the exploration of quantum mechanics precipitated transformative technologies such as atomic clocks, GPS, lasers, transistors, and magnetic resonance imaging (MRI). Meanwhile, the exploration of information theory brought about transformative advances in communication, computation, and data science. The confluence of these fields creates new scientific vistas to explore, with the compelling potential for new QIST 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,[142] 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 the field and its enabling

[141] *Science the Endless Frontier* (1945) https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm

[142] See the Quantum Frontiers Report (2020); federally funded QIS workshop reports; the 2019 White House Academic Roundtable on QIS; the 2018 White House Summit on QIS Summary: https://www.quantum.gov/wp-content/uploads/2021/01/2018_WH_Summit_on_QIS.pdf

technologies is prioritized as a means to produce new understanding, develop new capabilities, and 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:

Figure 4.2: In December 2022, OSTP hosted the NQI and NDAA QIS research centers to discuss the most pressing scientific and workforce challenges affecting quantum information science (QIS), as well as the impacts and benefits of the field for all of society. These centers compliment the broad and coordinated U.S. efforts from academia, federally funded research and development centers, and U.S. Government departments and agencies, which are accelerating American leadership in QIS and making progress on the six policy pillars laid out by the National Strategic Overview for QIS.

- 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, utilizes www.quantum.gov to help coordinate and showcase NQI activities.
- The SCQIS Science IWG and NQCO convened the fifth Federal QIS Program Day, bringing together QIS program managers, researchers, and stakeholders from across the Government to discuss projects and directions for QIS R&D.
- DOE's efforts in QIS span the technical breadth of its office of science, reflected in the diversity and scope of quantum R&D projects that focus on key topics in basic research in materials and photonics, quantum sensing, quantum computing, and quantum networking, as well as the exploration of quantum technologies' application space.
- DOE SC user facilities are also fully engaged in providing capabilities and expertise to serve users from the broader QIS research community, for both academic and industrial research, to ensure U.S. leadership in this field.
- NSF investments in QIS R&D are supported to a large extent by core programs across multiple in directorates including Biological Sciences, Computer and Information Science and Engineering (CISE), STEM Education, Engineering, Mathematical and Physical Sciences (MPS), Social, Behavioral, and Economic Sciences, and TIP. Core programs, such as the Atomic Molecular and Optical Experimental Physics programs in the MPS Division of Physics, and the Foundations of Emerging Technologies program in the CISE Division of Computing and Communication Foundations continue to be important mechanisms for supporting QIS R&D. NSF support for basic research in QIS also comes from the Office of Multidisciplinary Activities, Office of International Science and Engineering, and the EPSCoR office.
- NSF leverages several center-scale programs to support QIS, quantum engineering R&D, and quantum workforce development. For example, the QLCI program supports large-scale interdisciplinary research projects to advance the frontiers of QIS, fostering multidisciplinary approaches to specific scientific, technological, and workforce development goals in the field.

- Several other center-scale programs at NSF have historically supported QIS-related projects, including the Science and Technology Centers, Engineering Research Centers, Physics Frontier Centers, and Materials Research Science and Engineering Centers. It is anticipated that such center-level programs will continue and expand support for QIS projects in FY 2024.
- IARPA upholds the scientific approach as essential to the development of universal fault-tolerant quantum computing, by pursing investments in the underlying fundamentals of quantum error correction and fault-tolerance, through programs emphasizing co-development of theory and experiment.
- NIST has many foundational QIS research programs on both campuses (Gaithersburg and Boulder), as well as at universities participating with its joint institutes JILA, JQI and QuICS. NIST has strengthened and expanded these programs, which include theoretical and experimental scientific studies on complex physical systems and qubit types, quantum states of light, physics beyond 'the Standard Model,' exploring the boundaries of classical and quantum physics, the new physics and mathematics necessary for quantum information processing and characterization, technologies that underpin the deployment of QIS applications, material design, and QIS for biology and chemistry.
- NIH established a working group on QIS across the agency under the auspices of the NQI.[143] It has representatives from across 12 NIH Institute Centers and colleagues from DOE, NIST, and NSF to discuss joint opportunities on disruptive sensing and computing technologies for biomedical domains leveraging QIS.
- The DOD Basic Research Office and its Military Service counterparts, ARO, ONR, and AFOSR, have led foundational research in QIST for over three decades with both internal and external funding programs such as the Single Investigator programs, the Vannevar Bush Faculty Fellowship program, and MURIs. Single investigator programs and Young Investigator Programs run by ARO, ONR, and AFOSR in fields such as materials science, condensed matter, and atomic and optical physics provide a scientific backbone that underpins many QIS efforts.
- DHS S&T follows a science first approach to QIS in a number of ways and approaches QIS technologies with a critical and open mind. DHS S&T is engaged with the scientific community through conferences and workshops, as well as organizations such as the QED-C. DHS S&T also actively funds research in quantum computing metrics and benchmarks in order to better evaluate and assess quantum computing hardware as it develops. In August 2023, DHS S&T hosted the first annual Quantum Impacts Workshop that brings together experts, potential DHS quantum end-users and stakeholders, and representatives from agencies with QIS equities.
- The Quantum Networking IWG (QN-IWG) facilitates the implementation of the national strategy for *A Coordinated Approach to Quantum Networking Research*. This strategy includes four technical recommendations — (1) continue research on use cases, (2) prioritize cross-beneficial core components, (3) improve classical support capabilities, and (4) leverage "right-sized" testbeds — and three programmatic recommendations — (1) increase interagency coordination, (2) establish timetables for R&D infrastructure, and (3) facilitate international cooperation. A small sampling of some of the efforts include:
    - The QN-IWG workshop brought together 15 agencies to discuss progress and new opportunities in implementing the strategy; see Box 4.1.

[143] https://datascience.nih.gov/quantum-information-science

Box 4.1

The Quantum Networking IWG Workshop: The NQCO, under the auspices of the SCQIS and the QN-IWG, and NASA co-hosted a Quantum Networking Interagency Workshop. The workshop had attendance from 15 agencies, as well as DOE National Labs and NSF QLCIs with large quantum networking thrusts. The workshop was opened by Dr. Mackenzie Lystrup, Director of NASA GSFC, and Dr. Charles Tahan, Assistant Director for QIS at OSTP and Director of the NQCO. Dr. Lystrup highlighted the QIS efforts augmenting the NASA mission, as well as the future role that quantum science may play in deep space exploration and geoscience. Dr. Tahan re-emphasized the recommendations from the national strategy for *A Coordinated Approach to Quantum Networking Research* and the need to better understand the role that entanglement distribution will play in raising the fieldability of quantum devices. Participants of the workshop discussed the implications of the strategy on agencies, along with their institutions' R&D priorities, work being done to advance use-case development, workforce needs, collaborations, and novel R&D topics that have not been considered by the community at large.

These discussions were followed by breakout sessions covering domestic cooperation and coordination, critical components and the supply chain, near-term applications, international activities and considerations, and interoperability and standards of quantum networking. The discussions served not only as a retrospective into the two and a half years since the quantum networking strategy was released, but also offered a look toward the future as the QN-IWG prepares to execute the duties legislated by the CHIPS and Science Act for the Advancement of Quantum Networking and Communications Technologies in the United States.[144]

- DOE has made multiple awards and calls that have quantum networking thrusts, including, ASCR RENEW, ASCR Scientific Enablers for Scalable Quantum Communication, and the SBIR/STTR programs. In addition, DOE provides community resources such as its quantum networking testbeds and sponsoring the Quantum Computing and Quantum Networking Basic Research Needs workshop.
- The newly established DARPA QuANET program will develop the hardware, protocols, and software tools required for critical infrastructure, enabling the first viable transition strategy to operationalize quantum communications.
- NRL, ARL, USNO, NIST, NSA, NASA, and affiliate members consisting of the NIWC and AFRL, participate in DC-QNet, a fiber-based network that connects the six metropolitan agencies via a dark-fiber network to perform entanglement distribution at kilometer distances.[145]
- NSF Quantum Interconnect Challenges for Transformational Advances in Quantum Systems (QuIC-TAQS) program supports the development of components necessary to connect quantum devices on future quantum networks.
- NASA GSFC established the Goddard Quantum Network Initiative. The primary node provides an interface for orchestrating quantum networking resources between the Goddard Local Quantum Network and member nodes of DC-QNet.
- The AFRL quantum networking testbed spans basic and applied research across heterogeneous qubit technologies. Additionally, AFRL and AFOSR co-hosted the fifth Quantum for International workshop which advances international cooperation in open research, which had a quantum networking focus.

[144] The CHIPS and Science Act (Pub. L. 117-167) §§ 10661 (amending NQI Act to add new section 103(h), 15 U.S.C. §§ 8813(h)).
[145] https://www.nrl.navy.mil/Media/News/Article/3060477/nrl-announces-the-washington-metropolitan-quantum-network-research-consortium-d/

Box 4.2

Quantum Networking Components

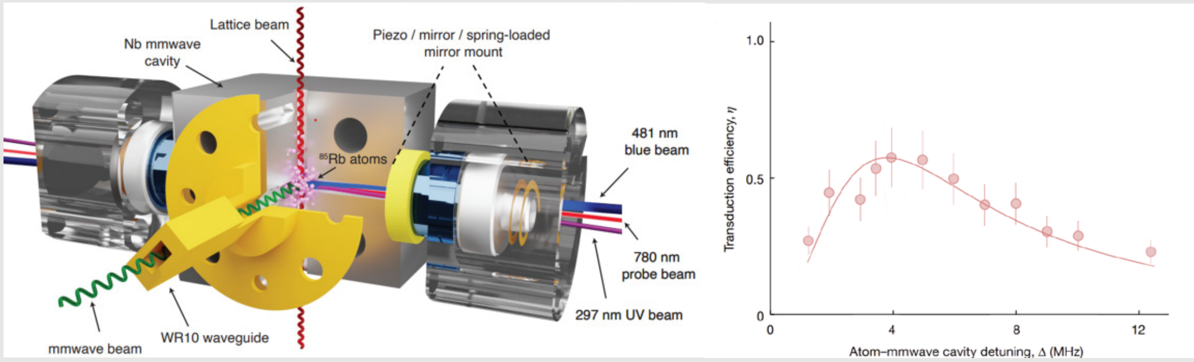

Figure 4.3: (Left) Apparatus for microwave to optical photon transduction with atoms trapped in crossed superconducting and optical cavities. (Right) Experimental data on transduction efficiency. [146]

Microwave to optical photon transduction with greater than 50% efficiency was demonstrated by researchers at the University of Chicago and Stanford University using cold Rydberg-dressed atoms trapped inside a superconducting cavity crossed with an optical cavity.[146] This approach incorporates features of superconducting circuits, cold atoms, and optical photons in a single device. Other approaches for microwave to optical photon transduction, e.g., using piezoelectric materials, electro-optical materials, and opto-mechanics, have demonstrated breakthroughs too.[147–152] Pioneering research in this area opens a new frontier in hybrid microwave/optical quantum science with prospects for producing metrologically useful entangled states, and for interconnecting superconducting qubits via optical fibers. These efforts align with the strategy for *A Coordinated Approach to Quantum Networking Research*, as they are creating new components that may enable networked quantum devices.

Funding for the research in described in this box was provided in part by the NSF QLCI for Hybrid Quantum Architectures and Networks, an NSF MRSEC Award, the NSF Graduate Research Fellowship Program, the ARO and AFOSR MURI programs, AFOSR, DARPA, and NIST, demonstrating a multi-agency support for quantum networking research.

- The national strategy for quantum sensing, *Bringing Quantum Sensors to Fruition*, released in February 2022 made four recommendations: (1) Agencies leading QIST R&D should prioritize partnerships with end users to elevate the technology readiness of quantum sensors, (2) Agencies that use sensors should conduct feasibility studies and jointly test prototypes with QIST R&D leaders, (3) Agencies that support engineering R&D should develop broadly applicable components and subsystems, and (4) Agencies should streamline technology transfer and acquisition practices. Some efforts to implement this strategy include:

[146] 'Quantum-enabled millimetre wave to optical transduction using neutral atoms,' doi:10.1038/s41586-023-05740-2; figure reproduced with permission from doi:10.48550/arXiv.2207.10121
[147] 'Cryogenic microwave-to-optical conversion using a triply resonant lithium-niobate-on-sapphire transducer,' doi:10.1364/OPTICA.397235
[148] 'Bidirectional interconversion of microwave and light with thin-film lithium niobate,' doi:10.1038/s41467-021-24809-y
[149] 'Optomechanical ground-state cooling in a continuous and efficient electro-optic transducer,' doi:10.1103/PhysRevX.12.021062
[150] 'Superconducting-qubit readout via low-backaction electro-optic transduction,' doi:10.1038/s41586-022-04720-2
[151] 'Superconducting qubit to optical photon transduction,' doi:10.1038/s41586-020-3038-6
[152] 'Microwave-to-optics conversion using a mechanical oscillator in its quantum ground state,' doi:10.1038/s41567-019-0673-7

- NSF announced grants totaling \$29 million to advance applications of quantum sensing though the QuSeC-TAQS program.
- DHS Science and Technology Directorate (S&T) is sponsoring the R&D of emerging quantum sensor technologies to strengthen national security and is assessing the utility of quantum sensors to support supply chain security of microelectronics and magnetometers to confirm the integrity of integrated circuits.
- NASA funded the Quantum Engineering and Sensor Technology Laboratory for R&D into Earth Science, Planetary Science, and Space Navigation and Timing.
- NASA's Engineering and Safety Center organized a quantum sensing workshop in September 2023 as part of an independent technical assessment of the agency's capabilities in quantum sensing and to understand NASA's internal needs and competencies related to sensing. The outcome of the assessment will help the agency in establishing appropriate strategies and investments to develop and maintain the state-of-the-art sensing competence and capabilities required to meet the agency's future needs.
- DOE announced multiple awards and solicitations relevant to quantum sensing: DOE BER's announced its interest in receiving applications for quantum enabled bioimaging and sensing approaches for bioenergy, DOE BER awarded \$18 million for research in Bioimaging and Sensing Approaches for Bioenergy, and DOE BER released a Transitioning Quantum Imaging and Sensing Technologies to Bioimaging Markets Research Study on QIST's potential to disrupt bioimaging.
- DARPA supports multiple programs pioneering R&D in quantum sensing such as AMBIIENT, A-Phl, SAVaNT, and QuIVER.
- During RIMPAC 2022, the DOD tested and demonstrated quantum sensors at sea for three weeks, showing promising signs of advancing the technology readiness of the platforms.
- NIH established a QIS and Quantum Sensing in Biology Scientific Interest Group,[153] to promote knowledge sharing in QIS and to provide a resource for NIH intramural scientists, fellows, graduate students, and interns.
- The QED-C produced a report Quantum Sensing Use Cases that provides an industry perspective to complement the National Strategy for Quantum Sensors.
- In January 2023, NIH held a Near-term Applications of Quantum Sensing Technologies in Biomedical Sciences workshop that brought together QIS and biomedical experts.[154] As an output of this workshop, the NIH working group on QIS and Quantum Sensing developed recommendations for NIH to engage end-users, bridge gaps between quantum technologies and biomedical fields, and develop the workforce. NIH also released a Notice of Special of Interest to support quantum sensing applications for biomedical fields. NIH is currently developing additional programmatic efforts to enable the adoption of quantum computing and sensing technologies in various biomedical fields.

4.2 Creating a Quantum-Smart Workforce for Tomorrow

The United States has built a strong foundation for QIS R&D over the past 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,

[153] https://oir.nih.gov/sigs/QIS-Quantum-Sensing

[154] https://datascience.nih.gov/news/nih-virtual-workshop-near-term-applications-of-quantum-sensing-technologies-in-biomedical-sciences

Federal laboratories, and quantum-related industries. Yet, in recent years this workforce has come under strain as the need for technical talent outstrips supply, with competing demands from industry, academia, and the Federal workforce. Furthermore, the growth that has occurred has not evolved to represent all of America, with many groups still being underrepresented.

To help ensure the United States creates a diverse, inclusive, and sustainable workforce that possesses the broad range of skills needed by industry, academia, national laboratories, and the U.S. Government, the SCQIS released a *QIST Workforce Development National Strategic Plan*.[155] This plan outlined four actions to help meet this goal:

- Action 1) Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives;
- Action 2) Introduce broader audiences to QIST through public outreach and educational materials;
- Action 3) Address QIST-specific gaps in professional education and training opportunities; and
- Action 4) Make careers in QIST and related fields more accessible and equitable.

The actions were supported with a set of recommendations for Federal agencies and opportunities for the broader QIST ecosystem. In support of this plan, agencies have been carrying out a series of activities to help develop the QIST Workforce. This list is not comprehensive, with other supportive actions being undertaken at national labs, academia, and industry.

Action 1: Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives

- NIST supports various QED-C workforce development activities, including on-going analysis of quantum industry workforce needs, an intern training program, a mentoring program, hosting student e-poster sessions, and career events, such as QED-C's 'Quantum Jobs' initiative that helps those considering a career in QIST to make connections and identify jobs in industry, academia, and government.
- DHS S&T regularly supports work for the larger quantum ecosystem to develop solutions for growing a quantum workforce. This involvement includes working with organizations such as QED-C (i.e., membership on the "Quantum Workforce Development" Technical Advisory Committee), as well as participation in invited talks and panel discussions at various conferences and workshops.
- The NQCO engages in bilateral and multilateral dialogues about international QIST workforce needs and potential ways for like-minded countries to collaboratively address talent shortages, including the launch of EntanglementExchange.org as a portal for international exchange opportunities in QIST.[156]
- NSF in coordination with other agencies on the SCIQS funded a project to study the education landscape for QIS and quantum engineering, with a focus on guiding education innovation to support career pathways in QIS and quantum engineering.

Action 2. Introduce broader audiences to QIST through public outreach and educational materials

To engage more people, earlier:

[155] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf
[156] https://entanglementexchange.org/

- Through the Q2Work award, led at the University of Illinois at Urbana-Champaign, NSF helped established a national program focused on education in quantum science at the K-12 level. This award created the National Q-12 Education Partnership that was launched by OSTP and NSF. Q-12 is a consortium that expands access to K-12 quantum learning tools and inspires the next generation of quantum leaders. Support for this activity continued in FY 2023.
- For World Quantum Day on April 14, 2023, agencies celebrated through social media posts, podcasts, webinars, blogs, "ask me anything" sessions, and more, reaching millions of people. See Box 4.3 for more information.
- NSA's LQC initiated multiple collaborative efforts with U.S. universities to advance curriculum and workforce development with the goal of building quantum awareness among students and partnering with post-secondary educators to align QIS education with QIS skills that are needed across industry and government.
- NIST activities at JILA, JQI, and QuICS involve direct engagement with universities and broader STEM outreach activities, such as with under-represented communities.

Action 3: Address QIST-specific gaps in professional education and training opportunities

To address knowledge gaps, agencies funded short courses and summer programs:

- NSA's LQC hosted its third annual Summer of Quantum short course from July 24 – August 4, 2023. This virtual two-week course introduces quantum computing to first- and second-year graduate students and qualified undergraduates in QIS-related fields.
- DOE SC awarded the first cohort of the Office of Workforce Development for Teachers and Scientists (WDTS) RENEW Pathway Summer Schools for high school and early undergraduate schools. Two of the five new Pathway Summer Schools will introduce high school students and freshmen to QIS topics in Summer 2023.
- The first joint summer school facilitated by the five DOE National QIS Research Centers — C^2QA, QSA, Quantum Science Center (QSC), Q-NEXT, and SQMS — was held August 6-15, 2023, at Fermi National Accelerator Laboratory. Participants learned about the Centers and their initiatives and were provided with unique hands-on training opportunities and integrated lectures in the emerging field of QIS. This program targeted undergraduate students, graduate students, postdocs, scientists, engineers, and technicians who are interested in learning about the field of QIS on both theoretical and practical levels.[157]
- The NIST SURF program inspires undergraduate students to pursue careers in STEM through research experience at NIST, with many projects focused on QIS.
- In February 2023, NIST co-organized the ⟨Q|School Single Photonics Short Course: Sources, Detectors and Measurements in Colorado.[158]

To increase QIST awareness with policymakers:

- DHS S&T created a DHS-wide Quantum Community of Interest (COI). This community makes the existing DHS workforce more quantum smart by raising the general level of awareness of QIS throughout DHS and providing regular educational opportunities to understand these emerging technologies and how they impact the DHS mission.

[157] https://sqmscenter.fnal.gov/opportunities/us-quantum-information-science-summer-school/
[158] https://www.colorado.edu/initiative/cubit/single-photonics-and-quantum-radiometry-short-course

Box 4.3

Agencies Celebrate World Quantum Day

On April 14, Federal agencies again participated in World Quantum Day, an annual international, grassroots celebration of quantum science. From social media posts to podcasts, webinars, blogs, and "ask me anything" sessions, agencies reached millions of people. A variety of promotional materials and resources were produced by agencies, including a free poster on Planck's constant,[159] flyers promoting ways to engage in World Quantum Day, and public domain graphics and images.[160,161]

OSTP, AFRL, DHS, DOE, the Department of State (DOS), NASA, NIH, NIST, NRL, and NSF participated in a coordinated interagency social media thread, where each agency responded to the previous about how quantum impacts their mission.[162] This elevated the reach of all agencies involved and demonstrated the whole-of-government approach to the NQI.

The National Q-12 Education Partnership, launched by NSF and OSTP, released a new video in celebration of World Quantum Day titled *What YOU Can Do with Quantum Science*. The video addressed questions about quantum science from middle school students and teachers, and it featured LeVar Burton, NASA astronaut Josh Cassada, and professional quantum scientists and students. The Q-12 also conducted its second annual QuanTime initiative to spur the adoption of quantum activities in K-12 classrooms, with activities supported by NSF, DOE, NASA, and industry. The Q-12, in partnership with a non-profit organization, launched the Quantum To-Go initiative to arrange for practicing quantum scientists to visit almost 140 classrooms.

Many Federal activities and resources for World Quantum Day are captured in a whitehouse.gov blog post and on quantum.gov. [163,164]

To create QIST experiences through internships:

- NASA QuAIL hosts over a dozen graduate student-level interns and research assistants each year to work on a research project together with a QuAIL team mentor for several months.

159 https://www.quantum.gov/wp-content/uploads/2023/01/PlancksConstant_Infographic_18x24_poster_size.pdf
160 https://www.quantum.gov/wp-content/uploads/2023/01/WorldQuantumDay2023_4WaysToEngage_Flyer.pdf
161 https://www.quantum.gov/quantum-image-gallery/
162 https://www.quantum.gov/happy-world-quantum-day-from-the-national-quantum-initiative/
163 https://www.whitehouse.gov/ostp/news-updates/2023/04/14/white-house-office-of-science-and-technology-policy-celebrates-world-quantum-day/
164 https://www.quantum.gov/world-quantum-day/

- DHS S&T directly helps train a future quantum smart workforce through its internship program.

To provide research opportunities for students and postdocs:

- NIST supports many students and postdocs working in the QIS arena through a range of programs. For example, the NIST NRC Postdoctoral Research Associateships Program has attracted top talent into NIST QIS programs, and many NIST NRC postdocs have gone on to become leaders in industry, academia, and government agencies and laboratories.
- NASA QuAIL hosted roughly fifty graduate students from the University College London and the University of Bristol at NASA ARC to participate in a series of hybrid remote and in-person talks from members. The students had an opportunity to learn about the QuAIL team's efforts in QIS, such as those in distributed quantum algorithms, blind quantum computing, quantum error mitigation, analog quantum algorithms, photonic simulations, and superconducting based quantum computers.
- IARPA funds research teams from academia, industry, and Government laboratories. Particularly at universities, these teams educate graduate students and mentor postdocs in areas critical to the future of quantum technologies, spanning relevant areas in physics, engineering, mathematics, and computer science.
- NSF focuses on the development of a broad-based, diverse workforce for QIST. NSF continued several of its existing, highly impactful workforce development programs in QIST in FY 2023, with an emphasis on training in the context of research. NSF supported approximately 1150 postdoctoral fellows, 4600 graduate students, 1400 undergraduate research students, and 45 high school students engaged in QIST research in 2023, aggregated across several programs.
- NSF's Graduate Research Fellowship Program (GRFP) continues to support Fellowships in a wide range of research disciplines, including areas that align with Administration priorities. Out of 2555 GRFP Fellowships in 2023, 47 were for quantum engineering or QIS research applications.[165]
- The NSF Research Traineeship Program is designed to encourage the development and implementation of bold, new, and potentially transformative models for STEM graduate education training. The program is dedicated to effective training of STEM graduate students in high-priority interdisciplinary or convergent research areas through comprehensive traineeship models that are innovative, evidence-based, and aligned with changing workforce and research needs. Awards fund a cohort of up to seven graduate students each year, for a period of five years. Out of the 70 traineeship program awards that were made from 2021 to 2023, 10 were for Quantum Information Science and Engineering themes.
- NSF's joint industry-academia graduate training program, known as QISE-NET, has established several "triplets," or three-person teams of university faculty, industrial researchers, and graduate students working on frontier QISE research projects.
- NSF issued Dear Colleague Letter (NSF-21-033) on Advancing Quantum Education and Workforce Development to highlight multiple programs focused on education that can support efforts in QIST education and training.
- The NSF QLCI activities include developing new curricula, classes and degrees, such as Master's Degrees in Quantum Science and Technology, an undergraduate minor in QIST, internship and summer programs for students, certificate programs for professional education and cross-training, opportunities for high school teachers to join QIS research teams each summer, multi-institutional partnership on curriculum development, liaisons with community colleges,

[165] https://www.research.gov/grfp/AwardeeList.do

experiences for the public such as museum exhibits and quantum-themed escape rooms, quantum lab tours for summer camps, and summer research opportunities for more students.
- DOE SC continued the support of undergraduate and graduate students in QIS areas via R&D grants, internships, and graduate thesis research.
- NASA and DHS S&T signed a MOU to collaborate on national efforts in QIST areas of research, including development of new technologies and applications, operation of and access to specialized facilities, and STEM education and workforce training.

Action 4: Make careers in QIST and related fields more accessible and equitable

To help grow capacity and get more people involved:

- In 2023, NSF continued the ExpandQISE thrust begun in FY 2022, which closely aligns with the QIST Workforce Development National Strategic Plan and encourages the participation of academic institutions not currently involved in or those underrepresented in the NQI.DOE has two new initiatives aimed at increasing participation from historically unrepresented groups and institutions, the FAIR program and the RENEW program. FAIR and RENEW are SC-wide initiatives across multiple SC research and workforce training programs, with QIS-related areas being a part of the portfolio.
- DOE SC's WDTS extended its existing Visiting Faculty Program from one to three terms and started offering two parallel tracks on research competitiveness and STEM teaching in DOE mission areas, including QIS. Through research collaborations with DOE national laboratories, faculty members from institutions historically underrepresented in STEM will be able to enhance research capacity and bring about impact on STEM teaching and students' learning at their home institutions.

To support careers:

- On September 14, 2022, all five DOE National QIS Research Centers participated in the C^2QA Quantum Career Fair. Over 490 students and postdoctoral researchers attended the fair to learn about the different careers in QIS at the Centers, National Laboratories, academia, and industry. C^2QA (and co-leads QSA and Q-NEXT) organized the third annual QIS Career Fair on September 13, 2023, with representation from all five QIS Centers, plus other agencies who participate in quantum R&D.[166]

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.

Successful translation of scientific discoveries into deployed technologies is challenging, and often requires 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 carefully supporting pathways and connections throughout the innovation community. Early-stage support to

[166] https://www.bnl.gov/nqisrccareerfair/

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.

- Agencies leverage SBIR and STTR programs to provide seed funding for early-stage R&D at startups and small businesses, including those seeking to market quantum technologies. In addition, CRADAs enable agencies to partner with many U.S. companies to accelerate the development of quantum technologies.[167]
- The innovation chain is one of five essential elements of the DOE National QIS Research Center programs. Each center has industry partners and include industry representatives on their advisory boards to ensure that the R&D conducted addresses challenges faced by the QIS commercial sector. In addition to participating in collaborative research, these partners enhance workforce development with internships and through mentoring junior participants.
- The DOE SC-wide lab-only announcement to Accelerate Innovations in Emerging Technologies supports basic research with a focus on expeditiously transitioning from discovery to commercialization of new technologies for future industries. It includes proposals combining advances in materials science, scalable synthesis, device architectures, and algorithms to enable next generation microelectronics or to transition emergent quantum materials used in computing and quantum technologies.[168]
- In 2019, NIST established the QED-C, using its Other Transaction Authority, in collaboration with SRI International, to enable and grow a robust commercial quantum-based industry and associated supply chain in the United States. NIST has an active seat on the QED-C Steering Committee. The QED-C is industry-led and now has activities addressing use cases for quantum, enabling technologies, standards and performance metrics, workforce development, legal aspects of quantum, and quantum for national security. Participation in the QED-C has grown to include more than 170 businesses, ranging from large, multinational corporations to small startups, 40 academic institutions and professional societies, and many U.S. agencies seeking quantum industry engagement. NIST and other U.S. agency scientists work within QED-C Technical Advisory Committees and as part of R&D teams helping address technical challenges faced by industry. The QED-C recently expanded its international engagement to 38 like-minded countries, helping establish and build the relationships needed to secure a trusted global supply chains and access to top talent.[169]
- NASA partnered with domestic and international industry members to collaborate on understanding and applying gate-based quantum computing processors to address complex computing challenges, develop noise models and error mitigation techniques, simulate approaches for realistic noise experienced by quantum hardware, and evaluate and characterize microchannel plate-photomultiplier tube detectors for space applications.
- DHS S&T deepens engagement with the quantum industry through its QIS COI. DHS S&T leverages the COI as a means of connecting operational components with potential industry partners advancing solutions that may meet their current and future needs. Internally, DHS S&T collaborates with operational components to understand their use cases that can potentially

[167] https://www.nist.gov/tpo/partnerships/cooperative-research-and-development-agreement-crada
[168] https://science.osti.gov/grants/Lab-Announcements/-/media/grants/pdf/lab-announcements/2023/LAB_23-3010.pdf
[169] https://quantumconsortium.org/membership/

benefit from quantum technologies. Meanwhile, the organization builds relationships with potential industry partners through conferences, working groups, and panels.

- IARPA makes awards through full and open competition, engaging the best of academia and industry. All of IARPA's quantum programs have involved and funded the quantum industry sector through prime and sub-prime contracts.
- Quantum technology is a major track of NSF's Convergence Accelerator program, now integrated within the NSF TIP Directorate. The Convergence Accelerator requires teams to leverage public-private and other types of partnerships to rapidly transition research outputs into practical quantum technologies with significant societal impact and develop convergent, trans-sector approaches to education and workforce development.
- The NSF Industry-University Cooperative Research Centers (IUCRC) program generates breakthrough research by enabling close and sustained engagement between industry innovators, world-class academic teams, and government agencies. NSF recently announced a set of IUCRC Awards for the Center for Quantum Technologies,[170] a partnership between Purdue University, Indiana University (both Bloomington and Indiana University Purdue University - Indianapolis campuses), and the University of Notre Dame, which will partner with industry and government stakeholders to identify compelling needs and challenges, and then develop novel quantum technologies to address them.
- NSF Regional Innovation Engines development awards were announced in May 2023 by the NSF TIP Directorate. Several Engines development awards include activities aligned with quantum science and engineering.[171]
- The NSF Q-AMASE-I Quantum Foundry program requires the foundries to engaging industry partners very closely with foundry operations and technological development activities to accelerate the development of the Nation's quantum technologies economic sector.
- The NSF QLCIs have over 65 commercial or industrial partners.

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:

[170] https://iucrc.nsf.gov/centers/center-for-quantum-technologies/
[171] https://new.nsf.gov/funding/initiatives/regional-innovation-engines

- NIST upgraded its Gaithersburg Center for Nanoscale Science and Technology and Boulder Microfabrication Facility, both of which provide researchers with access to state-of-the-art nanoscale measurement and fabrication tools and methods, along with associated technical expertise. NIST also upgraded laboratory facilities for quantum networking projects at both campuses, most notably to support DC-QNet.
- NIST, in partnership with DOD, developed a portable optical atomic clock for improved clock comparison, and is developing an optical lattice clock to contribute to U.S. and international timekeeping. Previously, all optical lattice clocks have been research-grade clocks that were continuously being improved, with limited operational time for official timekeeping.
- NASA and NIST are collaborating to develop world class quantum metrology capabilities for spaceflight. R&D is underway toward advanced techniques and instrumentation for the measurement of entanglement sources, quantum detectors, memories, and architecture with the specific focus of moving quantum technologies to space applications.
- NASA funded the Quantum Engineering and Sensor Technology Laboratory to develop, test, and evaluate capabilities for R&D into cold-atom-based sensors for earth science, planetary science, and space navigation and timing. This facility will house scientists and engineers to partner with industry, academia, and other government agencies to develop laser-cooled atomic gravity sensors and optical atomic clocks.
- NSA hosts the LQC Quantum Research Center which leverages collaborations between LPS personnel and extramural researchers to launch novel projects of a scope that neither group could pursue independently.
- NSA initiated the Qubit Foundry program to supply state-of-the-art qubits to U.S. researchers, removing the barrier to progress associated with the need for individual laboratories to invest in sophisticated fabrication equipment.
- DHS S&T aims to provide and secure critical infrastructure by exploring which quantum technologies would complement the DHS components' mission spaces. These include use cases within DHS components such as the Cybersecurity and Infrastructure Agency (CISA), as well as the U.S. Coast Guard (USCG), where quantum technologies could help secure critical infrastructure. DHS S&T is assessing the challenges faced by these components and whether quantum solutions can be provided for these missions and describing the likelihood of utility for these quantum technologies in the near future. One of the use cases identified is the need to maintain communications within critical infrastructure after an electromagnetic pulse event, which could be solved by the Rydberg atom electric field sensor's potential resilience to such an event. For the USCG, use cases have been identified for PNT needs in the case of GPS denial, which is also a large threat to critical infrastructure needs. Quantum solutions, such as quantum gravimeters, atomic inertial measurement units, and atomic clocks, provide potential alternatives in cases of incidental or intentional disruption of GPS signals.
- Advancements in critical quantum computing infrastructure — hardware and software — funded by IARPA for its research are also made available to other U.S. Government-funded programs, for their benefit in various quantum technology pursuits.
- Several of NSF's major research facilities and other research infrastructure investments enable research across QIS. Notable examples are NSF's National High Magnetic Field Laboratory and NSF's Center for High-Energy X-Ray Sciences,[172,173] both of which will continue to provide critical tools for frontier research in quantum materials.

[172] https://nationalmaglab.org/
[173] https://www.chess.cornell.edu/partners/chexs

- Several of the NNCI sites have formed a coordinated subgroup dedicated to the support of QIST-related research.[174]
- NSF backs nine MRSECs to create novel materials that can solve big challenges and enable the industries of tomorrow.[175]
- NRL and all 14 Naval Warfare Centers signed an MOU with the AFRL to connect the Navy R&D enterprise with the AFRL quantum computing hub, providing the Navy cloud-based access to quantum computers.
- The NSF STAQ co-design project aims to construct a practical quantum computer with a demonstrable advantage over current computer technologies. The project is co-designing and developing ion-trap quantum computing hardware and quantum algorithms by bringing together theoretical, experimental, and computer architecture experts.
- The NSF Q-AMASE-i program established a foundry in FY 2019 with mid-scale infrastructure for rapid prototyping and development of quantum materials and devices. A second foundry was established in FY 2021. The MonArk Quantum Foundry, led jointly by Montana State University and the University of Arkansas, brings to EPSCoR states together to accelerate two-dimensional materials research for quantum technologies in the United States. [176]
- In conjunction with industry partners, NSF is promoting the availability of cloud-based access to quantum-computing platforms to advance R&D and build capacity in the academic setting.[177]
- The NSF NQVL is conceptualized as an overarching shared infrastructure that aims to develop use-inspired and application-oriented quantum technologies and will be a flagship quantum testbed activity for the TIP Directorate. The NSF NQVL Solicitation is motivated by the challenge of demonstrating practical quantum advantages that can fulfill the QIST promise of a new, marketable technology. This program offers the connection between the NSF investments in basic science today into the promised technologies of the future. The call for the pilot phase of this project is being launched in FY 2023. NSF recognizes that the involvement of industry partners is essential and will welcome these partnerships into the overall structure.
- DOE IP advanced the construction of the U.S. Stable Isotope Production and Research Center at ORNL, which will use new electromagnetic isotope separator and gas centrifuge capabilities to significantly expand domestic stable isotope production, including for QIS. This capability will relieve U.S. dependency on Russia for enriched stable isotopes.
- In FY 2023, the DOE BES Nanoscale Science Research Centers received final funding for the development of infrastructure required for QIS research and to transition it to user programs. For example, the Quantum Material Press (QPress), a first-of-its-kind instrument for creating novel layered materials for quantum devices, was made available to users starting in FY 2022 and has supported research activities of 25 groups.[178]
- The DOE ASCR Quantum Computing Testbeds for Science program provides the research community with fully transparent access to novel quantum computing hardware systems that allow the research community to explore promising next-generation quantum processors that are not yet ready for industry uptake. DOE ASCR also supports two projects to develop and demonstrate regional scale — intra-city or inter-city — quantum internet testbeds.

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[174] https://nnci.net/
[175] https://new.nsf.gov/news/nsf-invests-162-million-research-centers?utm_medium=email&utm_source=govdelivery
[176] https://www.monarkfoundry.org/
[177] https://www.quantum.gov/nsf-funds-access-to-cloud-based-quantum-computing-platforms/
[178] https://www.bnl.gov/qpress/

- The DOE ASCR-funded Quantum Computing User Program provides access to cloud platforms for quantum computing through a merit-reviewed process, ensuring the research community has access to excellent cloud hardware for running the largest possible applications.
- Q-NEXT built two quantum foundries that serve as central resources for domestic, growth-to-integration control over materials and devices research for the center and other national quantum efforts. The foundry at Argonne National Laboratory provides synthesis, fabrication, deterministic placement, and characterization of spin qubit materials, including defects in diamond and silicon carbide. The foundry at the SLAC National Accelerator Laboratory is designed for research and fabrication of superconducting qubits, sensors, and devices, and includes six cleanroom bays. The foundries also contain novel testbeds and tools for quantum materials, devices, and component development.

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 QIST 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.

- ESIX provides a forum for agencies to discuss the national security implications of QIS and its enabling technologies. Through interagency and working group activities, ESIX is addressing the charge of the NDAA for FY 2022: (1) review and assess the economic security implications of QIS investments; (2) review and assess counterintelligence risks and foreign threats to the Nation's QIS portfolio; (3) assess the export of technologies associated to QIS; and (4) provide recommendations to mitigate risks resulting from the assessment of (1)-(3).
- In May 2023, the White House released its National Standards Strategy for Critical Emerging Technology (CET). It identified quantum technologies as an early-stage CET, and emphasized the importance of experts working to understand the appropriate time to promote technologically sound and impartial standards development.[179]
- NIST leads a broad effort to establish PQC standards that will enable encryption secure against attacks from both classical and quantum computers and be interoperable with existing communications protocols and networks. In August 2023, NIST released draft standards for three of the four PQC algorithms selected.
- NIST supports the QED-C Standards & Performance Metrics and Quantum for National Security TAC activities. For example, NIST is helping the QED-C develop Standardization Readiness Levels to enable the consortium to evaluate the potential impact of proposed standards and provide industry perspectives to U.S. standards developers. In addition, NIST actively engages with U.S. and international Standards Development Organizations (SDOs) on QIS.
- The *NIST Safeguarding Science Research Security Framework* establishes guidance to assist the U.S. science and research community across the broad spectrum of international science and technology activities as well as Federal funding initiatives.[180]

[179] https://www.whitehouse.gov/wp-content/uploads/2023/05/US-Gov-National-Standards-Strategy-2023.pdf
[180] 'Safeguarding International Science,' doi:10.6028/NIST.IR.8484

- DOE IP invests in technology development for the enrichment and production of isotopes critical to QIS R&D, increasing the Nation's indigenization of resources for QIS applications of importance to national security.
- DHS S&T is sponsoring the R&D of emerging quantum sensor technologies to strengthen national security. In particular, with the transforming Arctic region becoming an increasingly active operational area for the USCG and DOD, it is crucial to develop technologies that can support assured communications and high-accuracy sensing, while operating in the complex polar electromagnetic environment. DHS S&T is facilitating prototype development of quantum Rydberg atom electric field sensors for enabling wideband electromagnetic sensing with enhanced electronic support for applications including high-accuracy validation of high-frequency propagation models for over-the-horizon ionospheric communications and improved geolocation of marine rescue beacons.
- DHS S&T is assessing the potential utility of quantum sensors for applications supporting supply chain security of microelectronics and developing quantum-enabled magnetometers as a tool to confirm the integrity of integrated circuits fabricated offshore.
- IARPA maintains a robust Research Technology Protection program, which evaluates the research objectives for possible implications to national security. The potential for economic growth that a program could or would represent does not enter into decisions for research protection, yet researchers in the open nature of IARPA's quantum-technology programs have established U.S.-based startup companies in QIS-relevant fields.
- On behalf of NSF and OSTP, the Pittsburgh Quantum Institute hosted a workshop on the Cybersecurity of Quantum Computing which had breakout sessions to identify areas of R&D that would address hardware and software attacks and defenses for the security of quantum computers, as well as recognizing quantum algorithms that could be used for nefarious purposes.[181, 182]
- NSF issued a Dear Colleague Letter (NSF 23-098) to Request for Input on the Development of the U.S. Research Security and Integrity Information Sharing Analysis Organization (RSI-ISAO). The RSI-ISAO may support several topics including QIST research.
- The NSF Secure & Trustworthy Cyberspace (SaTC) program issued an RFI in March 2023 (NSF 23-063) for future directions for the program, including quantum computing.[183] PQC research will continue to be supported in the SaTC program.
- NSF issued Dear Colleague Letter (NSF 23-126) to inform the development of the NSF Research on Research Security Program (RRSP).[184] The RRSP can support topics including QIST research.

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 values through the conduct of research and education. QIS R&D is deeply international, with talent, infrastructure, and industrial capabilities globally diffused. More than three dozen countries around the world have significant Government funding for QIS research, and at least 17 have national strategies for

[181] https://www.pqi.org/news/workshop-cybersecurity-quantum-computing
[182] https://www.quantum.gov/wp-content/uploads/2022/11/2022-Workshop-Cybersecurity-Quantum-Computing.pdf
[183] https://www.nsf.gov/pubs/2023/nsf23063/nsf23063.jsp
[184] https://www.nsf.gov/pubs/2023/nsf23126/nsf23126.jsp

quantum technology development.[185] Accordingly, it is the policy of the United States 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.[186] By enhancing cooperation with those who share these foundational principles and values, we can ensure that the QIS capabilities of the United States and our close allies and partners remain strong, fostering a vibrant and secure international QIS ecosystem.

International collaboration is facilitated through several mechanisms. For instance, bilateral cooperation 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.

- 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 signed Joint Cooperation Statements for QIS with France, the Netherlands, the Republic of Korea, and Switzerland. These statements add to ones signed in previous years with Australia, Denmark, Finland, Japan, Sweden, and the United Kingdom. Each bilateral statement highlights the United States' commitment to building a vibrant international quantum ecosystem, embarking on good-faith cooperation, that is underpinned by our shared principles, including openness, transparency, honesty, equity, fair competition, objectivity, and democratic values.
    - The NQCO and DOS participated in two multinational roundtables on Pursuing Quantum Information Together: 2^N vs. 2N in November 2022 and March 2023, hosted by the United Kingdom and France, respectively. These roundtables facilitate conversations among government and national-level stewards of QIST R&D efforts and build on the event first launched by NQCO and DOS in May 2022.
    - As an output of the joint cooperation statements and the roundtables, Australia, Canada, Denmark, Finland, France, Germany, Japan, Netherlands, Sweden, Switzerland, the United Kingdom, and the United States launched the Entanglement Exchange,[187] a portal for highlighting international exchange opportunities for students, postdocs, and researchers in QIS. Since its launch, the Republic of Korea has been added to the Exchange.
    - In December 2022, the U.S.-EU Trade and Technology Council launched an expert task force on QIST to reduce barriers for collaboration and engage on several QIS-relevant issues.
    - The DOS Embassy Science Fellow program has sent U.S. Government employees from NIST, DOE, NSF, and DOS to Austria, Denmark, Finland, Germany, the Netherlands, Sweden, and Switzerland to foster international collaboration in QIST.
    - In December 2022, DOS announced its 2023–2024 cohort of Science Envoys, eminent scientists and engineers who leverage their expertise and networks to forge connections and

[185] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf
[186] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[187] https://www.entanglementexchange.org/

identify opportunities for sustained international cooperation. The 2023 cohort of includes the first dedicated quantum scientist to serve as a U.S. Science Envoy.

- International QIS activities are distributed across several U.S. government agencies, each pursuing QIS mission-specific collaborations, unilaterally or in partnership with additional agency partners.
    - International engagement in DOE's QIS programs continues to grow. The DOE National QIS Research Centers include institutions in Canada and Italy as full partners, and they have an increasing number of international affiliates making in-kind contributions to collaborative research projects. Additionally, ASCR's quantum computing testbeds have attracted interest from the international research community, with international collaborations selected in the most recent two calls for proposals. The DOE user facilities are open to all interested potential users without regard to nationality or institutional affiliation. In FY 2021, nearly 40 percent of the institutions that utilize the facilities were from outside the United States.
    - NASA collaborates internationally through MOUs and other mechanisms. For example, NASA is working with the European Space Agency on the Atomic Clock Ensemble in Space, which is expected to run tests of fundamental physics and launch to the International Space Station (ISS) in 2026. NASA and the Canadian Space Agency are cooperating on quantum optical communication between space and Earth. NASA and the Technical University of Delft signed an MOU to explore potential collaboration in quantum communications and networking, quantum sensors for applications in space-based science and observation, and observatories with ground and adaptive/synchronization capabilities. A similar arrangement has been signed with the Netherlands' Organisation of Applied Scientific Research. NASA HQ is also pursuing cooperation arrangements with Australia, Canada, France, and Qatar focusing on long-term joint efforts advancing QIS and STEM education, student and faculty exchange programs, and workforce training.
    - CAL on the ISS is a bilateral collaboration between Germany's Aerospace Center and NASA, designed to further expand on the experimental and scientific capabilities of CAL. As a multi-user, multi-purpose experimental facility, it will enable experiments such as dual-species atom interferometry for a test of Einstein's equivalence principle, the study of spinor and scalar Bose–Einstein condensate and gas mixtures, strongly interacting gases and molecules and many more. NASA Fundamental Physics also collaborates with the German Space Agency on the Direct Detection of Dark Energy in the Einstein Elevator, an atom interferometry experiment looking for direct evidence of certain proposed dark energy hypotheses.
    - NIST supports QED-C internationalization activities. The consortium now accepts participation applications from 38 like-minded countries, adding two more countries in 2023, and partners with similar international quantum industry consortia, such as, QuIC (European Union), QIC (Canada), and Q-STAR (Japan)).[188]
    - NIST regularly engages the international community and hosts delegations from other countries to discuss collaboration on QIS, most recently from Australia, Denmark, Italy, Japan, Singapore, South Korea, and the United Kingdom.
    - NIST works collaboratively with its peer NMIs around the world. NIST signed an MOU with the UK's National Physical Laboratory on joint QIS research opportunities. NIST chairs the recently formed Technical Committee 25 – Quantum Measurement and Quantum Information

[188] https://quantumconsortium.org/quantum-consortia-qic-qed-c-q-star-and-quic-form-international-council-to-enable-and-grow-the-global-quantum-industry/

of the International Measurement Confederation (IMEKO), providing a unique venue for NMIs to jointly advance quantum metrology.

- IARPA's portfolio includes U.S. teams and their international colleagues working closely together to advance the theoretical and experimental science relevant to quantum computing and quantum error correction.
- NSF supports collaborative international projects in QIS that are jointly funded by NSF and partnering organizations such as the Swiss NSF (see NSF 23-049)[189], the German DFG (see NSF 23-036),[190] the US-Israel Binational Science Foundation, (see NSF 20-094),[191] the Canadian NSERC (see NSF 22-031),[192] the British UKRI (see NSF 23-128), [193] the Indian DST (see NSF 23-114),[194] and the French ANR (see NSF 23-159).[195] Openness to new or ongoing coordination with international counterparts, as motivated by science research opportunities, is signaled in the Dear Colleague Letter NSF 14-099.[196] NSF invited requests for supplemental funding from existing QIS research awardees to add a new — or strengthen an existing — international dimension to their award, including short-to-mid-term visits (see NSF 22-108).[197]
- On October 12, 2022, DOS convened a U.S.–EU Joint Consultative Group meeting on S&T, which discussed a range of key topics including QIS talent and mobility.
- In December 2022, DOS organized a workshop convening QIS experts from academia, industry, and government to discuss topics including R&D challenges and commercializing fundamental research. The event was co-chaired by OSTP and Australia's Department of Industry, Science, and Resources. The workshop also seeded a subsequent quantum session during the February 2023 U.S.–Australia Joint Commission Meeting (JCM).
- In January 2023, DOS co-hosted the U.S.-Italy JCM on Science and Technology Cooperation, convening government, academic, and private sector experts from the DOE, NSF, and others to discuss S&T matters of mutual importance, including QIS and its potential to augment a broad spectrum of application spaces.
- In May 2023, the QED-C, in close coordination with DOS and OSTP, hosted a U.S.-India Quantum Dialogue, the first bilateral QIS engagement under the auspices of the U.S.-India Initiative on Critical and Emerging Technologies (iCET) launched by the White House.
- On May 16, 2023, OSTP, DOS, and the U.S. interagency joined the 15th U.S.-Japan Joint High Level Committee on S&T, which included QIS as a topic. A delegation of DOS, NIST, QED-C, and the U.S. Science Envoy also visited Japan's National Institute of Advanced Industrial Science and Technology to further discuss QIS.
- On May 19, 2023, agencies headed by Assistant to the President for Science and Technology and OSTP Director Arati Prabhakar met with Korean counterparts for the 11th U.S.-Korea JCM on S&T. Alongside the meeting was a public-private quantum roundtable — with participation from U.S. Science Envoy, QED-C, NIST, and DOS — that aimed to expand bilateral understanding and cooperation in QIS in follow-up to the April 25 signing of the U.S.-ROK Joint Quantum Statement.

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[189] https://www.nsf.gov/pubs/2023/nsf23049/nsf23049.jsp
[190] https://www.nsf.gov/pubs/2023/nsf23036/nsf23036.jsp
[191] https://www.nsf.gov/pubs/2020/nsf20094/nsf20094.jsp
[192] https://www.nsf.gov/pubs/2022/nsf22031/nsf22031.jsp
[193] https://www.nsf.gov/pubs/2023/nsf23128/nsf23128.jsp
[194] https://www.nsf.gov/pubs/2023/nsf23114/nsf23114.jsp
[195] https://www.nsf.gov/pubs/2023/nsf23159/nsf23159.jsp
[196] https://www.nsf.gov/pubs/2014/nsf14099/nsf14099.jsp
[197] https://www.nsf.gov/pubs/2022/nsf22108/nsf22108.jsp

5 Summary and Outlook

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

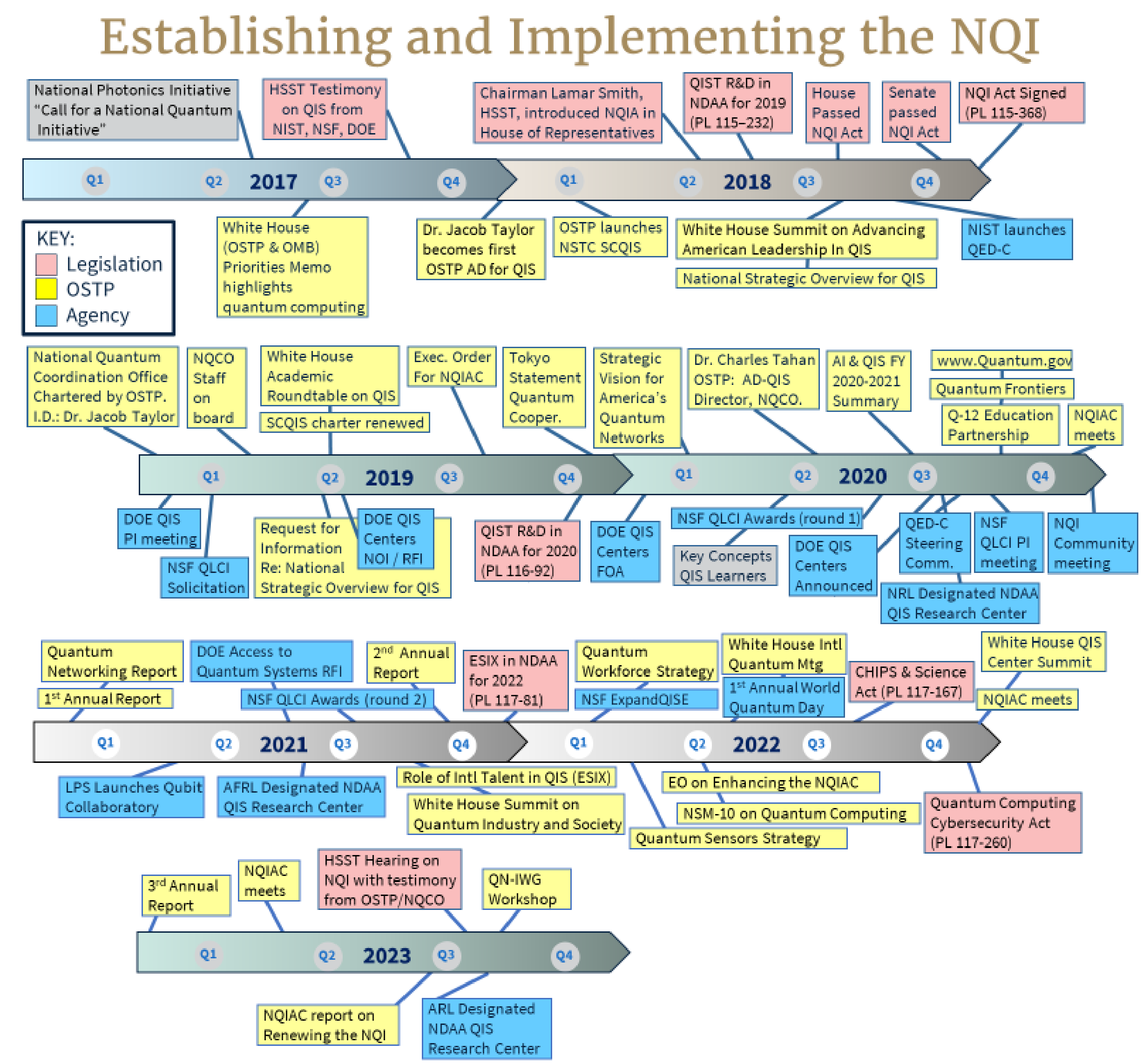

Figure 5.1: Timeline of actions establishing and implementing the NQI. Color-coding shows legislative process in red; OSTP and NSTC actions in yellow; agency actions in blue. The NQI was introduced in Congress, passed in the House, passed in the Senate, and signed into law by the President, reflecting bipartisan support. The 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 SCQIS and ESIX are highlighted in yellow. Agency actions on QIS R&D have been ongoing during this 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 prioritize 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.