# NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2023 BUDGET

*A Report by the*

**SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE**

**COMMITTEE ON SCIENCE**

*of the*

**NATIONAL SCIENCE & TECHNOLOGY COUNCIL**

January 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 2023 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 — that could yield transformative new types of computers, sensors, and networks, with the potential to improve the Nation's prosperity and security. Investments in fundamental QIS research lay a foundation for technologies of the future and open new frontiers in science.

> *"This increased research and development funding is going to ensure that the United States leads the world in the industries of the future: from quantum computing, to artificial intelligence, to advanced biotechnology." – President Biden, signing of the CHIPS and Science Act.*

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 research and development (R&D). The NQI Act also calls for coordination of QIS R&D efforts across the Federal Government, as well as with industry and the academic community.

Over the last year, the Biden-Harris Administration has taken major steps to continue accelerating U.S. leadership in QIS. In May, the President signed both an Executive Order to Enhance the NQI Advisory Committee and a National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems. Together, these orders emphasize the importance of a whole-of-government and whole-of-society approach to move the field forward, while taking important steps to mitigate any potential economic or national security risks.

This is the third annual report on the NQI Program and budget, as required by Section 103(g) of the NQI Act. This report follows a sustained investment in the NQI Program, building upon the establishment of several NQI centers, the Quantum Economic Development Consortium, and new QIS R&D activities. Agencies reported actual budget expenditures for QIS R&D of $449 million in Fiscal Year (FY) 2019, $672 million in FY 2020, and $855 million in FY 2021, followed by $918 million of enacted budget authority for QIS R&D in FY 2022, and a requested budget authority of $844 million for QIS R&D in FY 2023.

In line with the *National Strategic Overview for Quantum Information Science*, the United States is making substantial and sustained investments in fundamental QIS R&D to explore a wide range of applications and nurture a culture of discovery. Major efforts funded by several agencies are recognized in this report. Furthermore, overviews of agency efforts to progress on cross-cutting QIS policy topics such as investing in fundamental science and engineering, developing the workforce capacity, engaging with industry, investing in infrastructure, maintaining economic and national security, and encouraging international cooperation, are provided.

QIS can have profound and 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 all Americans have the opportunity to benefit from participation in QIS. Furthermore, while the development of QIS technology is at an early stage, now is a critical time to develop the fundamental scientific knowledge, infrastructure, and workforce needed to create new applications for QIS-inspired technologies, grow the marketplace, and foster an ecosystem for basic, applied, and translational research in this field.

# 1 Introduction

Quantum information science (QIS) builds on quantum mechanics and information theory to explore applications of quantum mechanics to computation, networking, and measurement. The improved understanding of the quantum world 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 1980's, pioneering QIS experiments since the 1990's, growth in quantum engineering capabilities since the 2000's, and the development of several commercial activities underway now, the world is on the cusp of a second quantum revolution. The potential for innovations based on QIS and the associated implications for jobs and security motivated the United States to enact the National Quantum Initiative (NQI) Act and increase QIS education and training opportunities.[1]

The NQI Act became law in 2018, "to provide for a coordinated Federal program to accelerate quantum research and development (R&D) for the economic and national security of the United States." The NQI Act authorizes the National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and Department of Energy (DOE) to strengthen QIS programs, centers, and consortia. The NQI Act also directs the coordination of QIS R&D efforts across the United States Government, including the civilian, defense, and intelligence sectors. To guide these actions, the NQI Act legislates several responsibilities to the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), the National Quantum Coordination Office (NQCO), and the National Quantum Initiative Advisory Committee (NQIAC).

Concurrently, the Defense Quantum Information Science and Technology (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 the Department of Defense's (DOD's) three-decade history of QIS R&D. The FY 2022 NDAA amended the NQI Act to codify the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX), as well as to legislate specific responsibilities to ESIX.[5]

The CHIPS and Science Act of 2022 further amended the NQI Act, authorizing additional activities for NIST, DOE, and 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.

The *National Strategic Overview for QIS* recommends strengthening the United States' approach to QIS R&D by focusing on six areas: science, workforce, industry, infrastructure, security, and international cooperation.[7] Since its publication, the strategy and these six policy pillars have been augmented by

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[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

[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://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

additional reports and plans, all of which are located at www.quantum.gov.[8] These activities build on Federal QIS R&D coordination via interagency activities such as those described in the 2009 NSTC Report on *A Federal Vision for QIS*,[9] the 2016 NSTC Report from the Interagency Working Group on QIS,[10] 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.[11]

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 the progress made by the quantum consortia, centers, and institutes established as part of the NQI.

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 NSTC Committee on Science. The SCQIS is co-chaired by the Office of Science and Technology Policy (OSTP), NIST, NSF, and DOE. Interagency discussions and recommendations by the SCQIS aim to strengthen U.S. leadership in QIS and its applications over the next decade. Members of the SCQIS are listed in the front matter of this document.

**The Subcommittee on Economic and Security Implications of Quantum Science (ESIX)** is co-chaired by OSTP, DOD, DOE, and the National Security Agency (NSA) and operates under the NSTC Committee on Homeland and National Security. In parallel with 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 research policy.

**The National Quantum Initiative Advisory Committee (NQIAC)** is the Federal advisory committee called for in the NQI Act to counsel the administration on ways to ensure continued American leadership in QIS. The NQIAC is tasked to provide an independent assessment of the NQI Program and to make recommendations for the President, Congress, and the Subcommittees to consider when reviewing and revising the NQI Program. The NQIAC is comprised of leaders in QIS from industry, academia, and the Federal Government. In 2022, a new Executive Order – 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.

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[8] https://www.quantum.gov

[9] https://www.quantum.gov/wp-content/uploads/2020/10/2009_NSTC_Federal_Vision_QIS.pdf

[10] https://www.quantum.gov/wp-content/uploads/2020/10/2016_NSTC_Advancing_QIS.pdf

[11] 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 2021 actual expenditures, FY 2022 estimated expenditures, and FY 2023 requested budgets. The U.S. QIS R&D Budgets have roughly doubled since FY 2019, with efforts catalyzed by the NQI Program. QIS R&D is also called for in the Multi-Agency R&D Priorities Memo for the FY 2023 Budget,[12] as well as the recent National Security Memorandum-10 (NSM-10),[13] and the 2022 CHIPS and Science Act.

Figure 2.1 shows overall Federal budgets for QIS R&D activities aggregated across several agencies such as 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 quantum consortia by NIST, Quantum Leap Challenge Institutes (QLCIs) by NSF, National QIS Research Centers by DOE, 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.

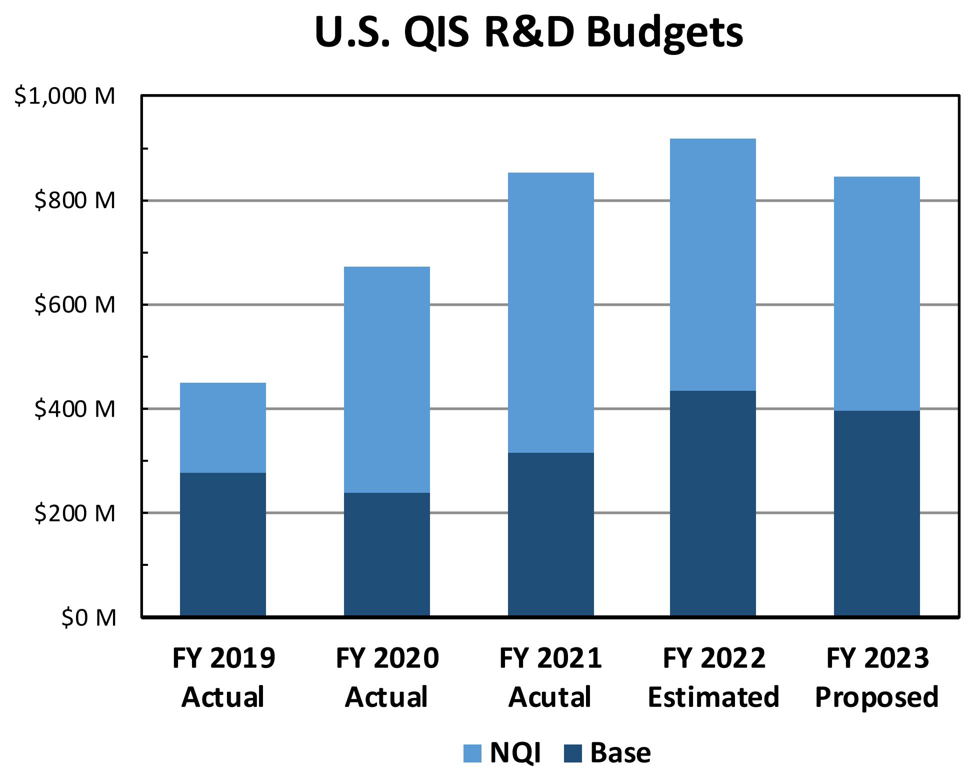

*Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQI Act. The bar heights represent the total budget for each fiscal year (FY 2019 – FY 2021 actual expenditures, FY 2022 estimated expenditures, and FY 2023 requested budgets). The portion of each bar marked "NQI" identifies funding allocated for NQI Act-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities.*

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

[13] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/

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. This can include uses of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by quantum control, for example, with atomic clocks.
- **Quantum Computing (QCOMP)** activities include the development of quantum bits (qubits) and entangling gates, quantum algorithms and software, digital and analog quantum simulators using programmable quantum devices, quantum computers and prototypes, and hybrid digital-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 QIS engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography (see Box 4.3).

Figure 2.2 shows budget allocations by NQI PCAs for FY 2019 – FY 2023 using a “layer-cake” bar chart for each year. A final breakdown for the budget data presented here shows QIS R&D budgets by agency. Figure 2.3 shows the total QIS R&D budgets for the three agencies prominently identified in the NQI Act: NIST, NSF, and DOE.

In summary, the budget charts show U.S. Government investments in QIS R&D. Respectively, Figures 2.1-2.3 present budget portions for NQI Act-authorized activities, NQI PCAs, and selected agencies. The data show an increased 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.

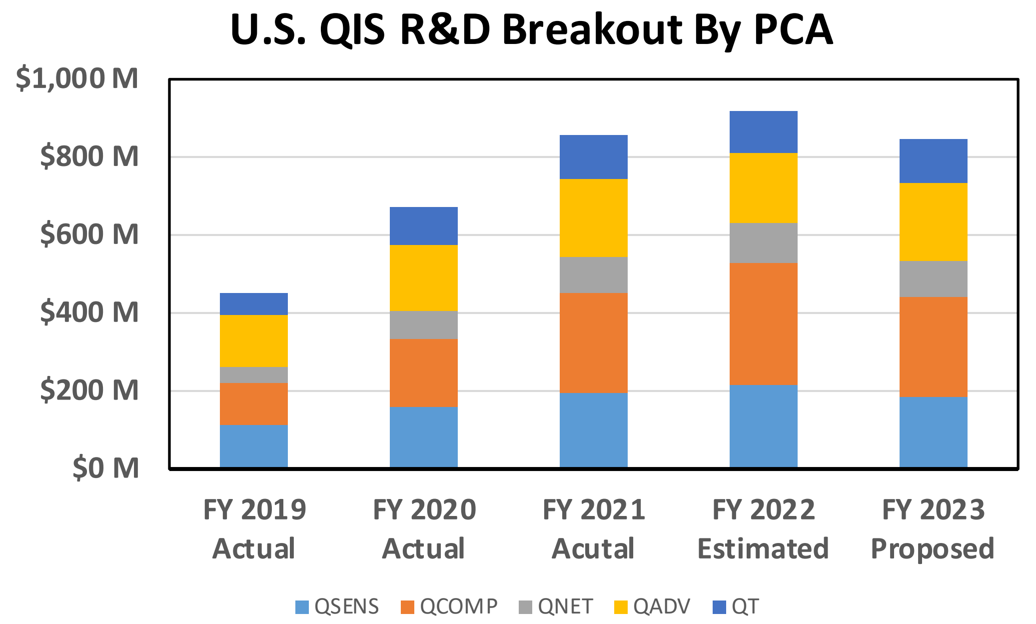

*Figure 2.2: U.S. QIS R&D budget allocations by NQI Program Component Area (PCA) for FY 2019 – FY 2021 actual expenditures, FY 2022 estimated expenditures, and FY 2023 requested budgets.*

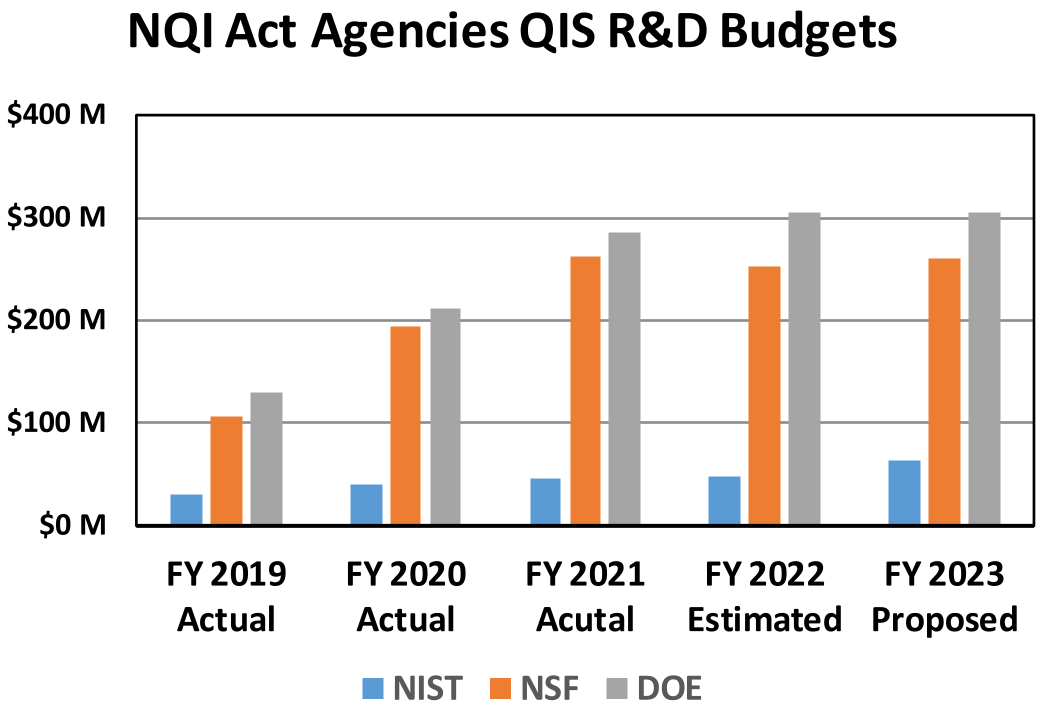

*Figure 2.3: QIS R&D Budgets for three agencies prominently identified in the NQI Act, showing FY 2019 – FY 2021 actual expenditures, FY 2022 estimated expenditures, and FY 2023 requested budgets.*

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 Act 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, uniting their collective efforts. The resulting ecosystem accelerates American leadership in QIST by simultaneously promoting discovery and exploration, while nurturing efforts to develop the market, supply chain, infrastructure, and the capacity to utilize quantum technologies.

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

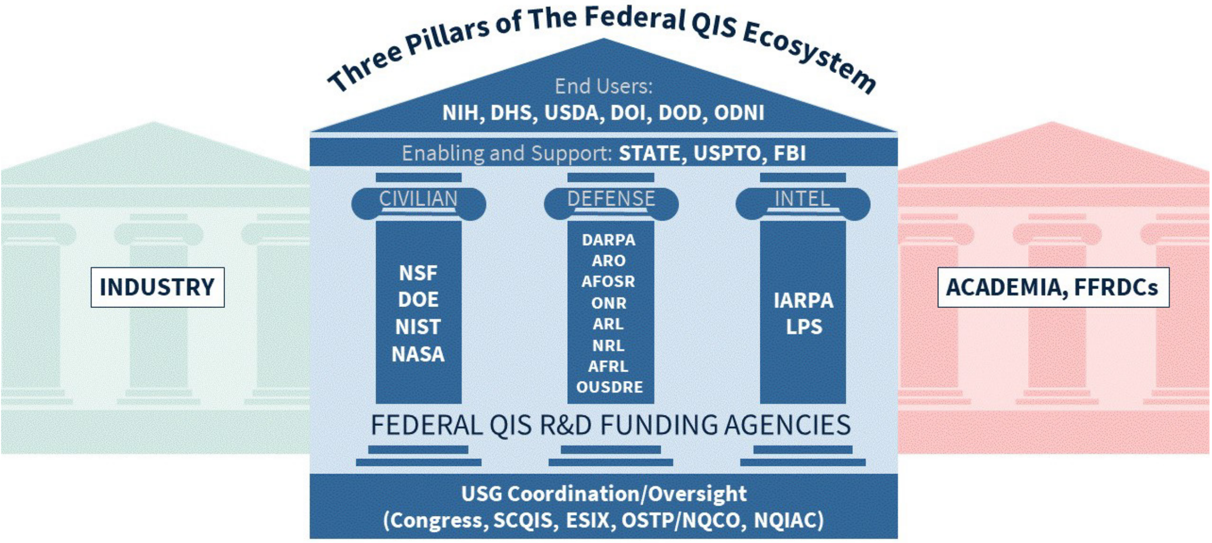

*Figure 2.4: Federal QIS R&D funding agencies can be seen as three pillars that support the Federal QIS ecosystem. Civilian science agencies (NSF, DOE, NIST, NASA) stand alongside DOD science agencies (OUSD(R&E), DARPA, ARO, AFOSR, ONR, ARL, NRL, AFRL) and the IC science agencies (IARPA, LPS) to collectively support QIS R&D efforts. Within the Federal Government, administrative support enabling the QIS ecosystem also comes from the FBI, USPTO, and DOS, and potential end users including NIH, DHS, USDA, DOI, DOD, and ODNI. Authorization, coordination, and oversight are provided by Congress, SCQIS, ESIX, OSTP, NQCO, and NQIAC. Pictured here as separate houses, Industry, Academia, and 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 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 their respective missions. 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 basic science, exploration, and the development of new technologies.

QIS R&D highlights are featured throughout this section, 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.

## 3.1 The National Institute of Standards and Technology (NIST)

Emerging quantum technologies pose new measurement challenges, but also offer previously unknown measurement solutions. 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. NIST conducts open, world-class research touching all elements of the national QIS agenda, with an emphasis on precision metrology and cybersecurity.[14] NIST has been a global leader in QIS research for over 25 years, beginning with seminal meetings at the Gaithersburg and Boulder campuses in 1994 and the NIST demonstration of the first quantum logic gate in 1995.[15] As authorized by the NQI Act, NIST advances QIS R&D through its core programs, including QIS R&D at NIST joint institutes, and coordinates an industry-focused consortium (the Quantum Economic Development Consortium, or QED-C),[16] which addresses quantum technologies, associated supply chains, and standards.[17,18,19] The NIST FY 2023 budget request includes “support [for] creating the quantum engineering ecosystem essential to create the industrial base for this future technology, train the future workforce, and transfer NIST technological knowledge to industry,” in parallel with the expansion of the foundational QIS research necessary to underpin engineering activities.[20]

**QIS R&D activities supported by NIST include:**

- NIST has internal basic and applied QIS research programs on quantum-enhanced sensing and precision measurement, quantum networking and communications,[21] quantum computing and simulation, fundamental physics, and scientific applications of quantum technology in chemistry, materials, biology, and healthcare. Areas targeted for expanded NIST QIS research include: (1) metrology of high-fidelity, large-scale quantum systems across multiple and hybrid physical platforms, and (2) materials research that connects material metrology to quantum system performance.

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[14] https://www.nist.gov/topics/quantum-information-science

[15] ‘Demonstration of a Fundamental Quantum Logic Gate,’ doi:10.1103/PhysRevLett.75.4714

[16] https://quantumconsortium.org/

[17] https://jila.colorado.edu/

[18] https://jqi.umd.edu/

[19] https://quics.umd.edu/

[20] https://www.commerce.gov/sites/default/files/2022-03/FY2023-NIST-NTIS-Congressional-Budget-Submission.pdf

[21] https://www.nist.gov/pml/quantum-networks-nist

- In response to a science-led QIS 'grand challenge' exercise, NIST established a quantum network program that includes developing multi-node testbed networks on its Gaithersburg and Boulder campuses; the Gaithersburg testbed is part of the multi-agency DC-QNet consortium.[22] These testbeds, which are under development, bring together NIST expertise and technology on trapped-ion and superconducting qubit technologies, single-photon sources and detectors, nano- and opto-mechanical quantum devices, optical frequency combs, and precision synchronization across free-space and fiber-based classical networks. The development of a scalable quantum repeater, which is a critical element needed for practical long-distance communication over quantum networks, is a particular focus.
- The NIST established QED-C enables and grows a robust commercial quantum-based industry and associated supply chain in the United States. The QED-C is industry-led and now has activities addressing QIS use cases, enabling technologies, standards and performance metrics, workforce development, legal aspects of QIS, and QIS for national security. NIST scientists work with the QED-C to address technical challenges faced by the industry. Today, the QED-C has participation from more than 165 businesses, ranging from large multinational corporations to small startups, 45 academic institutions and professional societies, eleven FFRDCs, and agencies seeking QIS industry engagement. The QED-C recently expanded its international engagement to 36 countries, helping build the relationships needed to secure global supply chains and access to top talent. NIST is supporting the QED-C in its effort to define "Standardization Readiness Levels" and apply them to QIS and related topics of vital interest to the industry, such as export control.
- NIST engages with industry through Cooperative Research and Development Agreements (CRADAs) that facilitate access to NIST laboratories and the transfer of technology.
- NIST's Center for Nanoscale Science and Technology (CNST) is a national user facility in which many types of QIS devices may be prototyped. NIST-Boulder has a leading microfabrication facility for superconducting devices and integrated photonics.
- 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's world-leading optical atomic clock program is a major contributor to international efforts toward the redefinition of the SI Second, and other applications of precision timekeeping and frequency standards. NIST chairs the newly 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.
- NIST's joint institutes—JILA with the University of Colorado Boulder, and the two joint institutes with the University of Maryland at College Park, the Joint Quantum Institute (JQI) and the Joint Center for Quantum Information and Computer Science (QuICS)—are major contributors to NIST's QIS workforce development efforts. The joint institutes provide world-class QIS instruction and research opportunities to undergraduate and graduate students, and postdoctoral researchers. A long history of collaboration with NSF, DOE, DOD, and the Intelligence Community (IC) (including substantial and sustained sponsorship by partner agencies) has enhanced research activities at NIST, especially at its joint institutes. NIST

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[22] https://www.nist.gov/news-events/news/2022/06/dc-area-us-government-agencies-announce-washington-metropolitan-quantum

researchers contribute to many of the NSF and DOE quantum centers, including Quantum Systems through Entangled Science and Engineering (Q-SEnSE) and Institute for Robust Quantum Simulation (RQS).[23,24]

- The NRC Postdoctoral and JILA Visiting Fellows programs provide additional opportunities for transformative post-graduate and early-career experiences, as well as collaborations with senior world leaders.
- The NIST on a Chip program brings cutting-edge measurement science technology and expertise from NIST laboratories to users in commerce, medicine, defense, and academia.[25] NIST has developed a diverse suite of inherently accurate quantum-based measurement technologies that can be deployed to users or embedded directly into products to reduce reliance on NIST's traditional measurement services.
- Since 2016, NIST has led an international competition-like standardization process for post-quantum cryptography (PQC) that recently culminated in the selection of four candidate algorithms for PQC standardization.[26,27] This activity is crucial to secure our public key infrastructure once a cryptoanalytically relevant quantum computer becomes available.

**NIST QIS R&D activities highlighted in the news:**

- (October 4, 2021) Researchers at JILA demonstrated a prototype sensor that uses a mid-infrared optical frequency comb and machine learning to simultaneously detect multiple biomarkers in human breath. The technology may offer practical real-time, noninvasive monitoring of a person's breath for clinical studies and early disease detection.[28]
- (December 14, 2021) A NIST research team, along with an independent international team, was awarded The Physics World "2021 Physics Breakthrough of the Year" for demonstrating entanglement between two macroscopic vibrating "drumheads." This advancement aides our understanding of the divide between quantum and classical systems, and provides new avenues for quantum transduction.[29]
- (December 20, 2021) Researchers at NIST and QuICS received the Universities Space Research Association Q2B "2021 Applied Noisy Intermediate Scale Quantum (NISQ) Computing Paper Award" for their analysis of three major approaches to quantum optimization.[30]
- (December 20, 2021) NIST and JQI researchers demonstrated a new technique in quantum many-body systems that can prevent quantum particles from reaching equilibrium, opening the possibility of many-body localization applications in robust quantum memory.[31]
- (February 16, 2022) NIST and JILA researchers measured time dilation at the smallest scale ever, showing that two tiny atomic clocks, separated by just a millimeter, tick at different rates; see Box 3.1 for more information.[32]

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[23] https://www.colorado.edu/research/qsense/
[24] https://rqs.umd.edu/
[25] https://www.nist.gov/noac
[26] https://csrc.nist.gov/Projects/post-quantum-cryptography
[27] https://csrc.nist.gov/News/2022/pqc-candidates-to-be-standardized-and-round-4
[28] https://www.nist.gov/news-events/news/2021/10/jilas-comb-breathalyzer-now-thousandfold-more-sensitive-disease-biomarkers
[29] https://www.nist.gov/about-us/nist-awards/physics-world-2021-breakthrough-year
[30] https://www.nist.gov/about-us/nist-awards/nist-paper-selected-2021-usra-q2b-applied-nisq-computing-paper-award-2021
[31] https://jqi.umd.edu/news/smooth-move-ions-ditch-disorder-and-keep-their-memories
[32] https://www.nist.gov/news-events/news/2022/02/jila-atomic-clocks-measure-einsteins-general-relativity-millimeter-scale

- (April 21, 2022) A team of NIST researchers demonstrated a readout protocol for atomic quantum computing that addresses the well-known crosstalk problem, a serious issue for large-scale fault-tolerant quantum information processing.[33]

**Box 3.1**

### Highlight: Optical Atomic Clocks Are Quantum Sensors

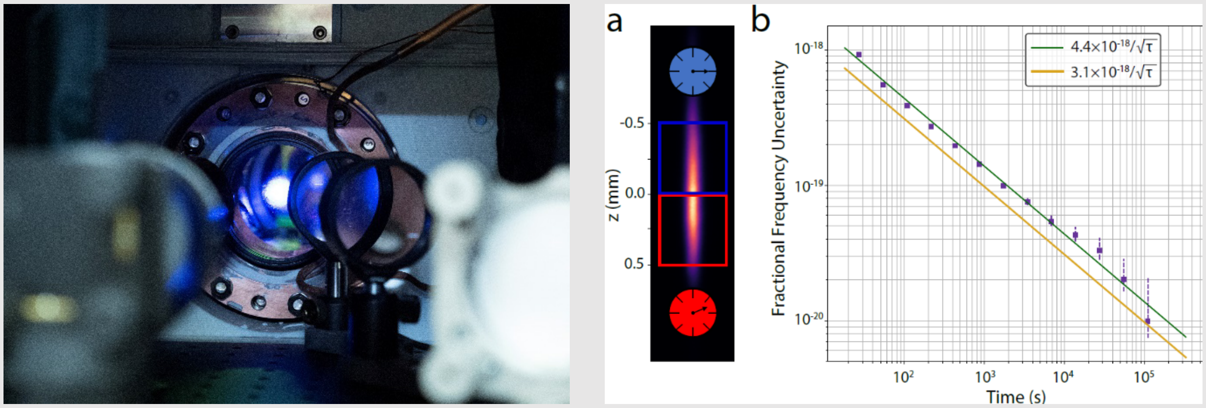

*Figure 3.1: (Left) An ensemble of ultracold strontium atoms, seen fluorescencing with laser excitation.*[34] *(Right) (a) A cloud of laser cooled strontium atoms at JILA is loaded into an optical lattice to form two optical atomic clocks spaced less than a millimeter apart in height. Because of the gravitational redshift, the upper clock ticks faster than the lower clock. (b) The fractional uncertainty in the frequency difference between the two clocks when averaged over 92 hours.*[35]

Einstein's theory of general relativity explains that gravity warps spacetime so that clocks at different points in space, where gravity is different, will not tick at the same rate. This effect is known as "gravitational redshift" and means that clocks at different heights (i.e., different distances from the Earth) tick at slightly different rates. A JILA research team formed optical atomic clocks that were spaced vertically at a submillimeter distance apart and observed the difference in the rates the clocks ticked due to this gravitational redshift.[31] By taking advantage of record quantum coherence times, this sensing application of optical atomic clocks measured a fractional frequency with uncertainty at a record level of $10^{-21}$. Increased precision and accuracy in the measurement of time has a wide range of applications, including improved navigation. This project leveraged previous investments made by DARPA, NSF, DOE, and AFOSR.

- (April 25, 2022) NIST optical atomic clock technology is a leading contributor to international efforts to redefine the fundamental unit of time: the SI Second. The SI Second will not get longer or shorter, but will be much more precise.
- (May 4, 2022) In connection with JILA, NIST demonstrated exceptional control and manipulation of a complex atomic species in an optical tweezer array, paving the way for improved neutral-atom quantum computing, simulation, and sensing.[36]

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[33] 'High-Fidelity Indirect Readout of Trapped-Ion Hyperfine Qubits,' doi:10.1103/PhysRevLett.128.160503

[34] Image credit: JILA

[35] Images reproduced with permission from 'Resolving the Gravitational Redshift Across a Millimeter-Scale Atomic Sample,' doi:10.1038/s41586-021-04349-7

[36] https://jila.colorado.edu/news-events/articles/tweezing-new-kind-qubit

- (May 12, 2022) NIST supported the creation of the first-ever quantum technology manufacturing roadmap through a grant to SRI International, its partner in the establishment of the QED-C, to identify gaps and barriers in pre-competitive development and supply chains for advanced manufacturing of quantum-related devices, components, and systems in the United States.[37]
- (June 15, 2022) NIST, in conjunction with JILA, developed a new opto-mechanical device to demonstrate that quantum information stored in a superconducting circuit can be read out with minimal impact. This low-noise feature is a crucial requirement for leading quantum networking protocols.[38]
- (July 1, 2022) A NIST research team integrated several quantum elements into a single device to demonstrate fast, efficient, low-power modulation of microwave light, providing a new approach to the transduction of quantum information between microwave and optical domains needed for networking superconducting quantum devices.[39]
- (July 05, 2022) NIST announced the first four quantum-resistant cryptographic algorithms, which will become part of NIST's PQC standard and is expected to be finalized over the next two years.[40]
- (July 12, 2022) NIST, together with international-partner NMIs, is working toward the realization of high-precision standards both within laboratories and in the form of miniaturized, intrinsically accurate and quantum-referenced sensors.[41]
- (July 13, 2022) NIST Fellow and Director of the NSF QLCI Q-SEnSE was awarded the DOD Vannevar Bush Faculty Fellowship, the DOD's most prestigious single investigator award.[42]

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[37] https://www.nist.gov/news-events/news/2022/05/nist-awards-funding-strengthen-advanced-manufacturing-critical-and-emerging

[38] https://jila.colorado.edu/news-events/articles/connecting-microwave-and-optical-frequencies-through-ground-state

[39] 'Quantum phase modulation with acoustic cavities and quantum dots,' doi:10.1364/OPTICA.451418

[40] https://www.nist.gov/news-events/news/2022/07/nist-announces-first-four-quantum-resistant-cryptographic-algorithms

[41] 'The expanding role of National Metrology Institutes in the quantum era,' doi:10.1038/s41567-022-01659-z

[42] https://www.nist.gov/awards/2022-vannevar-bush-faculty-fellow-jun-ye

## 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.[43] In the field of QIS in particular, NSF is currently funding over 1,500 projects at more than 240 institutions in 48 states led by over 2000 investigators. These QIS research projects are collectively training over 3000 graduate students, who are exploring fundamental concepts and applications for quantum computing, networking, and sensing.[44]

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 www.nsf.gov/quantum.[45] NSF's FY 2023 budget request to Congress articulates three goals for investments in QIS: (1) "Answer key science and engineering questions to facilitate the fundamental understanding of quantum phenomena and systems, as well as the translation of that fundamental knowledge into technological applications;" (2) "Deliver proof-of-concept devices, applications, tools, or systems with a demonstrable quantum advantage over their classical counterparts that will form the basis of a revolutionary 21st-century technology;" and (3) "Empower the full spectrum of talent to which NSF has access to build needed capacity and generate the quantum-literate workforce . . . in ways that will enhance the diversity of that workforce through the inclusion of members of groups heretofore underrepresented in the endeavor."[46]

**QIST R&D Programs at NSF:**

- Quantum Leap Challenge Institutes (QLCIs) (Solicitation NSF 19-559) are large-scale multidisciplinary centers for QIS engineering, research, and education.[47]
- Expand-QISE (Solicitation NSF 22-561) increases research capacity and broadens participation in the United States QIS and engineering endeavor. It provides support to build and maintain close connections between new efforts and already-impactful existing QIS centers or research institutions. Creating and nurturing a critical mass of QIS talent at more institutions is an intentional goal of the Expand-QISE program.
- Transformational Advances in Quantum Systems (TAQS) programs support teams of three or more investigators with collaborative, interdisciplinary projects that apply QIS engineering concepts. TAQS solicitation topics include Quantum Sensing Challenges (NSF 22-603),[48] Quantum Interconnects (NSF 21-553), a Quantum Idea Incubator (NSF 19-532), and a pilot opportunity (NSF 18-035).[49]
- Core programs fund many research activities related to QIS in a wide variety of disciplines, including computer science, engineering, biology, and mathematical and physical sciences. The "Connections in QIS" webpage provides a partial list of such programs.[50] These programs, which support projects led by individual investigators, small-scale research teams, and in some cases awards to individuals, as in the Quantum Computing & Information Science Faculty Fellows program, serve as important sources of new ideas and are crucial sources of support underpinning QIS research. These awards also serve as a gateway for including individuals and

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[43] https://nsf.gov/news/factsheets/Factsheet_By%20the%20Numbers_05_21_V02.pdf

[44] Statistics are based on information provided by Principal Investigators in annual reports to NSF on QIS-related projects.

[45] https://www.nsf.gov/quantum

[46] https://www.nsf.gov/about/budget/fy2023/pdf/fy2023budget.pdf

[47] https://beta.nsf.gov/funding/opportunities/quantum-leap-challenge-institutes-qlci

[48] https://beta.nsf.gov/funding/opportunities/quantum-sensing-challenges-transformational

[49] https://www.nsf.gov/awardsearch/simpleSearchResult?queryText=TAQS

[50] https://beta.nsf.gov/funding/opportunities/connections-quantum-information-science-cqis

institutions that are not currently engaged in QIS research, especially those at MSIs and emerging research institutions.

- Other large-scale QIS 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 Center for Integrated Quantum Materials (CIQM) at Harvard University, the multi-institutional Software-Tailored Architecture for Quantum co-design (STAQ) project led by Duke University, the multi-institutional Enabling Practical-Scale Quantum Computing (EPiQC) project led by the University of Chicago, the multi-campus research and education cluster on Emergent Quantum Materials and Technologies (EQUATE) led by the University of Nebraska, and several Materials Science and Engineering Center (MRSEC) projects focused on quantum technologies such as the Princeton Center for Complex Materials, the Columbia Center for Precision-Assembled Quantum Materials (PAQM), the Penn State University Center for Nanoscale Science, 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.

**NSF QIS R&D activities highlighted in the news:**

- (2021 – 2022) NSF issued several Dear Colleague Letters describing opportunities to advance quantum education and workforce development (NSF 21-033),[51] utilize quantum computing platforms remotely via CloudBank (NSF 22-092),[52] grow an international component of existing QIS projects (NSF 22-108),[53] explore quantum device or component manufacturing (NSF 21-074),[54] support graduate student internship activities (NSF 21-013), explore solutions to climate change that utilize quantum technologies (NSF 21-124),[55] and apply for computer and information science and engineering CSGrad4US fellowships (NSF 22-061).
- (February 1, 2022) NSF Director Sethuraman Panchanathan said, "To accelerate growth in quantum science and engineering, we must continue to institutionalize and scale efforts that create a culture of creativity and inclusivity, one that empowers people from all backgrounds and disciplines to pursue quantum careers."[56] These remarks were part of his welcoming address at the “Quantum Workforce: Q-12 Actions for Community Growth” event organized by the White House OSTP’s NQCO and NSF. The event convened educators and QIST leaders to expand training and education opportunities for America’s future QIST workforce, in alignment with the QIST Workforce Development National Strategic Plan.[57]
- (March 16, 2022) NSF announced the formation of a Directorate for Technology Innovation and Partnerships (TIP), the first new NSF directorate in 30 years.[58] The TIP Directorate includes several programs such as the NSF Convergence Accelerator, Innovation Corps (NSF I-Corps™),

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[51] https://nsf.gov/pubs/2021/nsf21033/nsf21033.jsp
[52] https://nsf.gov/pubs/2022/nsf22092/nsf22092.jsp
[53] https://nsf.gov/pubs/2021/nsf21090/nsf21090.jsp
[54] https://nsf.gov/pubs/2022/nsf22074/nsf22074.jsp
[55] https://nsf.gov/pubs/2021/nsf21124/nsf21124.jsp
[56] https://beta.nsf.gov/news/white-house-office-science-technology-policy-and-us-national-science-foundation
[57] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf
[58] https://beta.nsf.gov/news/nsf-establishes-new-directorate-technology-innovation-and-partnerships

America's Seed Fund (which includes SBIR and SBTR programs), and the Regional Innovation Engines (NSF Engines) program that can support QIS engineering and technology activities.

Box 3.2

### Highlight: Programming a Neutral-Atom Quantum Computer

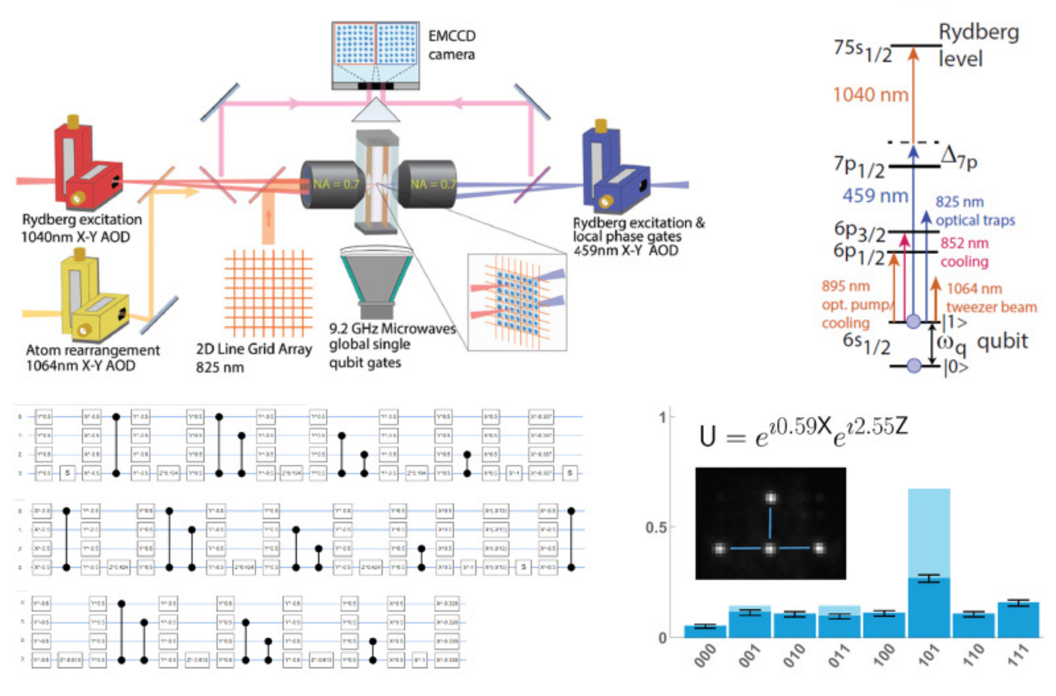

*Figure 3.2: Researchers implemented quantum algorithms on a neutral-atom quantum processor.*[59]

Quantum computing with neutral-atoms use sophisticated traps for individual atom qubits, and Rydberg-level-assisted interactions between groups of atoms. This approach opens new scientific and engineering opportunities to create systems with 1-D, 2-D, or 3-D lattices of qubits using novel gate sets based on the Rydberg blockade effect. This platform is complementary to trapped ions or superconducting qubit systems, with several university teams and a few startup companies pioneering quantum processors based on neutral atoms.

Quantum algorithms encoded in gate-model digital circuits on a programmable neutral-atom processor were recently demonstrated, as shown in Figure 3.2, along with entangled Greenberger–Horne–Zeilinger states with up to six qubits, quantum phase estimation for chemistry, and a quantum optimization algorithm. The researchers concluded, "these results highlight the emergent capability of neutral-atom qubit arrays for universal, programmable quantum computation, as well as preparation of non-classical states of use for quantum-enhanced sensing."

This project leveraged synergistic investments from the DARPA Optimization with NISQ Devices program, the NSF QLCI program, a grant from an NSF core program on QIS, an award from DOE, and earlier investments from IARPA. Two startup companies also collaborated on this project, and the publication acknowledged investment from Innovate UK's Sustainable Innovation Fund Small Business Research Initiative, demonstrating international cooperation.

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[59] Images reproduced with permission from 'Multi-qubit entanglement and algorithms on a neutral-atom quantum computer,' doi:10.1038/s41586-022-04603-6

- (May 1, 2022) The Center for Quantum Technologies was funded through NSF's Industry-University Cooperative Research Centers Program. This collaboration between Purdue University, Indiana University, the University of Notre Dame, and Indiana University–Purdue University Indianapolis, has the overarching vision of bringing together multidisciplinary experts in academia, industry, and the Government to facilitate the transition of fundamental research discoveries in QIS into technologies ready for commercial use.[60]
- (June 27, 2022) NSF announced 27 awards through its research traineeship (NRT) program that focus on artificial intelligence and QIS. The NRT program trains graduate students in interdisciplinary areas to align with evolving workforce needs.[61]

Box 3.3

## Highlight: Quantum Metrology with Many-Body Entangled States

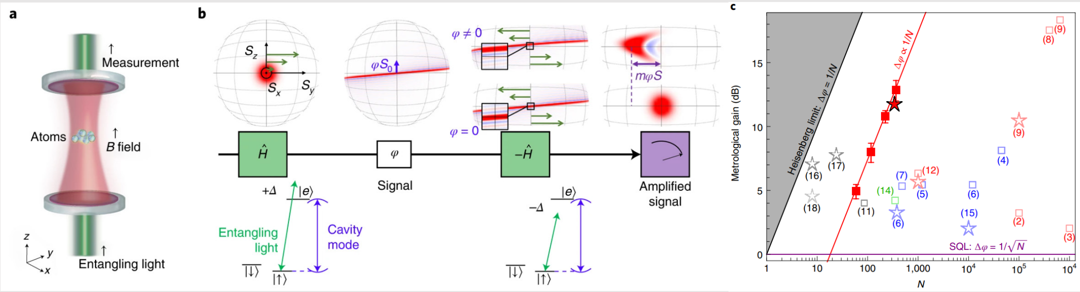

*Figure 3.3: Spin squeezing followed by a time-reversed process of "unsqueezing" amplifies a signal. (a) Dispersive interaction with light in an optical cavity causes squeezing. (b) It manifests as a twist, or sheering operation, for atoms' collective spin represented on a Bloch sphere. (c) The resulting metrological gain allows measurements beyond the Standard Quantum Limit.*[62]

Quantum sensors can use entanglement to improve precision measurements. Metrological gain due to entanglement has been reported using Bose Einstein condensates, thermal atoms, trapped ions, Rydberg atom arrays, and squeezed light. However, it remains a challenge to engineer metrologically useful entanglement and readout of the resulting quantum states. A novel process for doing this is shown in Figure 3.3.

Researchers recently implemented a protocol named "signal amplification by time-reversal interaction" to go beyond the Standard Quantum Limit (SQL) and demonstrate Heisenberg scaling. The procedure starts with spin squeezing, followed by applying the signal to be measured in between coherent operations that first squeeze and then unsqueeze the collective spin. It is well-known that a squeezed state has reduced uncertainty in one quadrature. What the researchers showed is that a small displacement φ along the squeezed quadrature can be amplified due to coherent many-body dynamics involving entanglement. The final "unsqueezed" state is displaced by $m\varphi$ where $m$ is called the metrological gain.

This project was funded by NSF, ONR, and DARPA. The demonstration sets the stage for improved measurements that may be useful for timing, geodesy, tests of fundamental physics, and further advances in quantum engineering. Importantly, it showcases an advantage for metrology based on the use of coherent many-body entangled states.

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[60] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2052730

[61] https://beta.nsf.gov/news/nsf-research-traineeship-program-expands-include-43-states

[62] Images reproduced with permission from 'Time-reversal-based quantum metrology with many-body entangled states,' doi:10.1038/s41567-022-01653-5

## 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, isotope production, and scientific innovation. The DOE National Laboratories are a system of outstanding intellectual assets, unique among world scientific institutions, that also serve as regional engines of economic growth for States and communities across the country.[63] As authorized by the NQI Act, DOE established five National QIS Research Centers and is continuing to strengthen and coordinate QIS research throughout its core programs.

The DOE Office of Science's (SC) QIS website https://science.osti.gov/Initiatives/QIS provides public access to SC-sponsored workshop reports and to detailed information about SC QIS programs.[64] Outreach activities funded by SC and conducted by DOE's National Laboratories are also advertised and have received a strong positive response from the community.[65]

**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 to ongoing QIS research conducted by the DOE National Nuclear Security Administration.

The DOE SC Program Offices QIS web pages,[66] last year's Annual Report on the NQI Program,[67] and DOE FY 2023 Budget request[68] contain broad discussions 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 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 for QIS includes infrastructure development in DOE user facilities such as the Nanoscale Science Research Centers, and the development and stewardship of technologies for producing isotopes needed for quantum systems.

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[63] https://science.osti.gov/Laboratories
[64] https://science.osti.gov/Initiatives/QIS
[65] https://www.quantum.gov/action/large-qis-efforts/#National-Laboratory-QIS-Pages
[66] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages
[67] https://www.quantum.gov/wp-content/uploads/2021/01/NQI-Annual-Report-FY2021.pdf
[68] https://www.energy.gov/sites/default/files/2022-04/doe-fy2023-budget-in-brief-v6.pdf

With a well-established merit-review-based access policy, DOE user facilities continue to support QIS research by offering a suite of advanced resources.[69] Additionally, Oak Ridge National Laboratory's (ORNL) Quantum Computing User Program provides access to industrial quantum computing resources to a broad user base,[70] while DOE SC's Quantum 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 (LBNL).[71,72] DOE also supports two projects to develop and demonstrate regional scale – intra-city or inter-city – quantum internet testbeds.

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.

**DOE QIS R&D activity highlights:**

Funding announcements:

- (November 12, 2021) The DOE SC BER program, through its Bioimaging Research effort, released a Funding Opportunity Announcement (FOA) for Quantum-Enabled Bioimaging and Sensing Approaches for Bioenergy, focused on advancing fundamental research and use-inspired technologies that exploit quantum phenomena in new bioimaging or sensing approaches.[73]
- (April 14, 2022) The DOE SC ASCR program released an FOA for EXPRESS: 2022 Exploratory Research for Extreme-Scale Science with two QIS topics, Quantum Algorithms and Mathematical Methods and Quantum Computing at the Edge.[74]
- (May 25, 2022) The DOE SC ASCR program released an FOA for Reaching a New Energy Sciences Workforce (RENEW) which will leverage ASCR's unique national laboratory infrastructure to increase participation and provide workforce training and research opportunities in quantum computing and networking to students, postdoctoral researchers, and faculty from underrepresented groups in the ASCR portfolio, such as non-R1 institutions of higher education and MSIs, including Historically Black Colleges and Universities (HBCU).[75] As a part of the RENEW program, the DOE SC held two community networking workshops hosted by LBNL and ORNL intended to address these issues in QIS.[76]

R&D for Supporting Technology:

- The DOE SC IP has developed new methods for producing stable isotopes of ytterbium-171 and silicon-28, which are relevant to quantum memory and quantum computation, respectively. Furthermore, the DOE Isotope Program 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 that are necessary for many QIS technologies.

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[69] https://science.osti.gov/User-Facilities
[70] https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/
[71] https://qscout.sandia.gov
[72] https://aqt.lbl.gov
[73] https://science.osti.gov/-/media/grants/pdf/foas/2022/SC_FOA_0002603.pdf
[74] https://science.osti.gov/-/media/grants/pdf/foas/2022/SC_FOA_0002717.pdf
[75] https://science.osti.gov/-/media/grants/pdf/foas/2022/DE-FOA-0002767.pdf
[76] https://sites.google.com/lbl.gov/renew-networking-events/home

Community Resources:

- (2021-2022) The DOE SC NP program, through its InQubator for Quantum Simulation (IQuS) award, brings people together to create and exchange ideas and to gain deeper understandings of nuclear physics, quantum information, and quantum simulation.[77] Six workshops have been held addressing key challenges and recent advances in QIS including topics in Quantum Error Mitigation for Particle and Nuclear Physics, Scientific Quantum Computing and Simulation on Near-Term Devices, and Next-Generation Computing for Low-Energy Nuclear Physics: from Machine Learning to Quantum Computing.[78]
- (December 2021) The DOE SC ASCR program held the Quantum Computing Testbeds Stakeholder Workshop. The topics included operational requirements for near-term testbeds, guiding the design of future testbeds, integrating new research advances, supporting technologies, fostering the quantum workforce, and opportunities for collaboration, international efforts, and related programs within the United States and industry.[79]
- (January 12-13, 2022) All five DOE National QIS Research Centers participated in the Workshop on DOE User Facilities for QIS, which explored leveraging the DOE National Laboratory facilities for QIS.[80]
- (May 18-20, 2022) Two DOE-funded National QIS Research Centers, The Quantum Science Center (QSC) and the Superconducting Quantum Materials and Systems Center (SQMS), and an NSF Focused Research Hub in Theoretical Physics, the Center for Quantum Information and Control (CQuIC) at the University of New Mexico, held a quantum algorithms workshop to facilitate collaboration between the centers.[81]
- (August 19-21, 2022) The DOE National QIS Research Center for Next-Generation Quantum Science and Engineering (Q-NEXT) co-hosted the Third Workshop for Quantum Repeaters and Networks in Chicago. The goal of the workshop was to discuss the progress, challenges, and possible new directions for quantum repeaters and networks.[82]

**Box 3.4**

**Quantum Career Fair:** In September 2021, all five DOE National QIS Research Centers participated in the Co-design Center for Quantum Advantage ($C^2QA$) Quantum Career Fair. Over 350 students and postdoctoral researchers attended the fair to learn about the different careers in QIS at the Centers, National Laboratories, academia, and industry. Based on the success of the 2021 event, starting in 2022, this Career Fair will be sponsored and organized annually by all five Centers.[83]

QIS R&D in the News:

- (December 2021) The DOE SC NP program, through its "Quantum Horizons: QIS Research and Innovation for Nuclear Science" effort, supports open scientific research in QIS to enable

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[77] https://iqus.uw.edu/
[78] https://iqus.uw.edu/workshops/past-workshops/
[79] https://web.cvent.com/event/fab5041a-48a6-44e9-a1ba-876e93ce44be/summary
[80] https://q-next.org/doe-user-facility-workshop-jan-12-13/
[81] https://cquic.unm.edu/events/2022/05/qaw.html
[82] https://chicagoquantum.org/wqrn3
[83] https://www.bnl.gov/nqisrccareerfair/

discoveries that explore and understand all forms of nuclear matter. One result of this effort is that DOE-funded researchers have devised the “quantum rodeo” algorithm which is exponentially faster than other well-known algorithms and is a promising candidate for future studies of quantum many-body systems in nuclear physics, particle physics, condensed matter physics, atomic and molecular systems, and quantum chemistry.[84]

- (January 14, 2022) As part of an international effort, DOE researchers demonstrated more than 99 percent fidelity for “if-then” logic gates between two silicon qubits. The technique combined the results of many separate experiments to create a detailed snapshot of the errors in each logic gate.[85]
- (April 2022) DOE researchers built a quantum local area network to share information among three systems in separate buildings using entangled photons and remote state preparation, performing this protocol across all paired links in the network.[86]

**Box 3.5**

### Highlight: New Error Mitigation Approach helps Quantum Computers Level Up

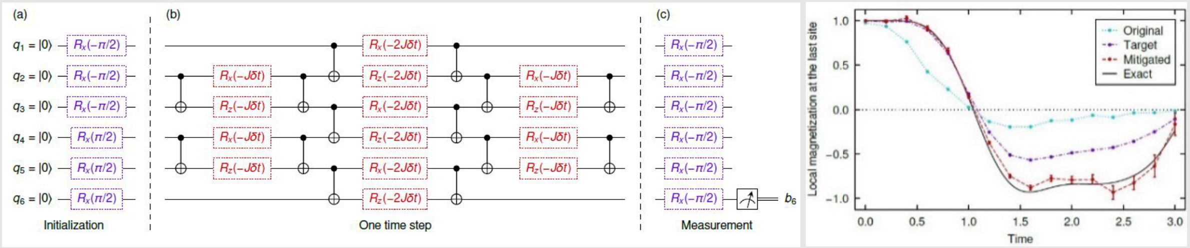

*Figure 3.4: Researchers demonstrated a new quantum error mitigation approach by simulating the evolution of a chain of six spins (left). The error-mitigated results are much closer to the exact results than the original measured data from the quantum computer (right).*[87]

Quantum computers have the potential to solve complex problems much faster than classical computers, but currently environmental noise causes too many errors for the computers to be consistently useful. While error correction would be the ideal solution, it is not yet feasible on current quantum computers due to the number of qubits needed.

Quantum error mitigation on the other hand, uses alternative methods and software to minimize errors in quantum simulations. Researchers at LBNL developed a new approach to quantum error mitigation: noise estimation circuits. A circuit is a series of operations, or a program, executed on a quantum computer used to calculate the answer of a scientific problem. The team used a modified version of the circuit to estimate errors and correct the output measured for the real scientific simulation of the intended circuit. While the noise estimation circuit approach corrects some errors, it does not correct them all. By combining the new approach with three other error mitigation techniques, the researchers were able to obtain reliable results on a commercial quantum system.

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[84] https://www.energy.gov/science/np/articles/quantum-rodeo

[85] https://science.osti.gov/ascr/Highlights/2022/ASCR-2022-03-a

[86] https://science.osti.gov/ascr/Highlights/2022/ASCR-2022-04-a

[87] Images reproduced with permission from ‘Mitigating Depolarizing Noise on Quantum Computers with Noise-Estimation Circuits,’ doi:10.1103/PhysRevLett.127.270502

## 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 fourteen critical technology areas and has been a focus of sustained DOD funding for thirty years. DOD continues substantial investments in basic QIS R&D activities via several offices, agencies, and laboratories including: the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), the Defense Advanced Research Projects Agency (DARPA), the Army Research Laboratory (ARL), the Army Research Office (ARO), the Naval Research Laboratory (NRL), the Office of Naval Research (ONR), the Air Force Research Laboratory (AFRL), and the Air Force Office of Scientific Research (AFOSR).

**DOD QIS R&D activity highlights:**

- DOD quantum R&D programs span atomic clocks, quantum sensing, quantum computing, and quantum networking, from fundamental to applied R&D:
    - Atomic clocks R&D programs across the 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: the ONR Next-Generation Atomic Clock (NGAC) program,[88] the ARL Low-Cost Chip-Scale Atomic Clock (LC CSAC) program,[89] the AFRL Quantum Sensing and Timing program, and the United States Naval Observatory (USNO) timekeeping research for the USNO Master Clock.
    - 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,[90] as well as the DARPA Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT),[91] Atomic-Photonic Integration (A-PhI),[92] Science of Atomic Vapors for New Technologies (SAVaNT),[93] the Quantum Apertures,[94] and the Quantum Imaging of Vector Electromagnetic Radiation (QuIVER) programs,[95] the Army's Metrology program, ARL's Electromagnetic Field Sensing with Rydberg Atoms program,[96] ARO's Quantum State Engineering for Enhanced Metrology and Multi-Qubit Enhanced Sensing and Metrology Multidisciplinary University Research Initiatives (MURIs),[97] ONR's atom interferometry efforts for inertial and gravity sensors, the AFRL Strategic Atomic Navigation Devices and Systems (SANDS),[98] and the AFOSR MURI on Cold Molecules.

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[88] https://www.onr.navy.mil/-/media/Files/Funding-Announcements/Special-Notice/2020/N00014-20-S-SN17.ashx
[89] https://www.arl.army.mil/lccsac/
[90] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/
[91] https://www.darpa.mil/program/atomic-magnetometer-for-biological-imaging-in-earths-native-terrain
[92] https://www.darpa.mil/program/atomic-photonic-integration
[93] https://www.darpa.mil/program/science-of-atomic-vapors-for-new-technologies
[94] https://www.darpa.mil/program/quantum-apertures
[95] https://www.darpa.mil/program/quantum-imaging-of-vector-electromagnetic-radiation
[96] https://www.army.mil/article/242980/army_researchers_detect_broadest_frequencies_ever_with_novel_quantum_receiver
[97] https://www.cto.mil/wp-content/uploads/2020/02/fy2020-muri-press-release.pdf
[98] https://afresearchlab.com/technology/quantum/

  - Quantum Computing is expected to address long-term military challenges in areas such as access to high-performance computing and cryptographic solutions. Ongoing basic research efforts include DARPA programs on Optimization with NISQ devices (ONISQ),[99] Quantifying the Utility of Quantum Computers (Quantum Benchmarking), and Underexplored Systems for Utility-Scale Quantum Computing (US2QC),[100] 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 augment access to high-performance computing. The DOD service labs (AFRL, ARL, and NRL) have efforts in heterogenous quantum networking R&D including photonic, atomic/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 DC-QNet. Quantum networking programs include 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.
- 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.
- Delaware State University, a HBCU/MSI, is a Center for Excellence in Advanced Quantum Sensing supported by OUSD(R&E) and managed by ARL.[101] Increasing diversity and inclusion in QIST research is a priority for the DOD.

**DOD QIS R&D activities highlighted in the news:**

- (February 3-4, 2022) AFOSR released two STEM education funding opportunities, a STEM FOA and DURIP-LL which could be used for QIS.[102,]
- (February 10, 2022) DOD released a funding announcement for FY 2023 MURIs that include topics on Quantum Phononics, Dislocations as One-Dimensional Quantum Matter, and Control Theory for Novel Quantum Error Correction.[103]
- (Feb 22, 2022) DARPA launched the US2QC program with the goal of determining if new and innovative approaches to quantum computing are capable of achieving utility-scale operation much faster than conventional predictions.[104]
- (February 23, 2022) The DARPA Proposers Day for the new Robust Optical Clock Network (ROCkN) program which seeks to transition precision optical atomic clocks, with timing

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[99] https://www.darpa.mil/news-events/2020-05-11a
[100] https://www.darpa.mil/news-events/2021-04-02
[101] https://www.cto.mil/news/dod-launches-center-of-excellence-in-advanced-quantum-sensing/
[102] https://www.grants.gov/web/grants/view-opportunity.html?oppId=337849
[103] https://www.arl.army.mil/wp-content/uploads/2022/04/W911NF-22-S-0007-Amendment-1-MURI-FOA.pdf
[104] https://www.darpa.mil/news-events/2022-02-22

accuracy and holdover better than GPS, from the laboratory to the warfighter.[105]

- (March 7, 2022) AFOSR released a FY 2023 funding announcement for a Young Investigator Program with a special emphasis on the new LPS-AFOSR partnership in Quantum Computing.[106]
- (June 30, 2022) DARPA hosted the Quantum-Classical Networking Interoperability Workshop with the goal of engaging subject matter experts in quantum and classical networking to discuss the integration of new quantum networking technologies with existing network infrastructures, along with practical, near-term use cases.

**Box 3.6**

### Highlight: Multi-Band Radio Frequency Quantum Sensing with Rydberg States

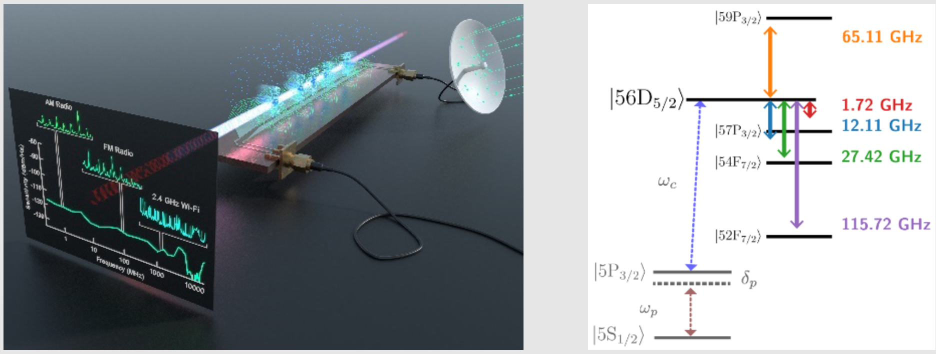

*Figure 3.5: (Left) Artistic representation of a waveguide-coupled Rydberg-based spectrum analyzer. (Right) Energy level diagram of a multi-band Rydberg receiver.*[107, 108]

Rydberg-based sensors have unique properties, including broad carrier frequency coverage (DC to THz), high precision, large dynamic range, and optical readout. In the near-term, these sensors could serve as a radio frequency (RF) calibration standard, and have a potential future application of being a single passive RF sensor with a widely tunable range. ARL demonstrated the world's first Rydberg-based communications receiver in 2018 as a part of the Office of the Secretary of Defense's Quantum Science and Engineering Program. This effort has led to two new DARPA programs (Quantum Apertures and SAVaNT) aimed at advancing this new quantum sensor's capabilities and identifying applications.

In 2021, ARL demonstrated a Rydberg spectrum analyzer as illustrated in Figure 3.5. This device used atoms coupled to a custom RF waveguide, enabling for the first time a continuously tunable measurement from 0 to 20 GHz, having peak sensitivity better than -145 dBm/Hz, and performance that is continuing to improve. Further advances in 2022 include a Rydberg sensor modeling software package, developed in collaboration with the Navy, that is now being used across agencies and private companies, and the demonstration of simultaneous multi-tone operation with a single Rydberg receiver over six octaves, from 1.7 GHz-116 GHz, under the DARPA Quantum Apertures program. Collaborative work with an FFRDC developed a simplified laser stabilization technique that reduces SWaP-C, eliminating cumbersome and expensive laser locking equipment. Ongoing fundamental research efforts aim to increase modulation bandwidth, frequency agility, and improve sensitivity towards quantum limits, while preserving the sensor's unique properties.

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[105] https://www.darpa.mil/news-events/robust-optical-clock-network-proposers-day#:~:text=The%20Defense%20Advanced%20Research%20Projects,Clock%20Network%20(ROCkN)%20program.

[106] https://www.grants.gov/web/grants/search-grants.html?keywords=FOA-AFRL-AFOSR-2022-0005

[107] Images reproduced with permission from ARL

[108] 'Simultaneous Multi-Band Demodulation Using a Rydberg Atomic Sensor,' doi:10.48550/arXiv.2208.10287

## 3.5 The National Aeronautics and Space Administration (NASA)

NASA continues to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. NASA's quantum research portfolio includes several activities in a number of directorates at NASA headquarters such as the Space Technology Mission Directorate (STMD), Science Mission Directorate (SMD), and the Space and Operations Mission Directorate (SOMD), supported by NASA's Glenn Research Center, Ames Research Center, Goddard Space Flight Center, and Jet Propulsion Laboratory (JPL). NASA partners with other government agencies, academia, national laboratories, and FFRDCs, and actively pursues international partnerships for cooperation across the entire spectrum of quantum science and technology as well as its application spectrum.

### NASA QIS R&D activity highlights

- NASA STMD released a new solicitation for university-based consortia for Space Technology Research Institutes (STRI), with one of the two main solicited topics being Quantum Technologies for Remote Sensing, driven by potential applications in astrophysics and earth science.[109] STMD is also exploring new applications and requirements for climate science missions into the 2030s for future quantum sensing applications, including those based on atom interferometry.
- NASA SMD's Biological and Physical Sciences Division funded the International Space Station (ISS)-based Space Entanglement and Annealing Quantum Experiment (SEAQUE). SEAQUE will test the response of photon detectors and receivers in the harsh radiation environment of space and will also test a technique meant to help space-based quantum nodes "self-heal" from space radiation damage. The SEAQUE collaboration includes scientists and students from academia, industry, and NASA's JPL, and the ISS-based experiment has an anticipated launch date of March 2023.
- NASA's Space Communications and Navigation (SCaN) Program of the Space Operations Mission Directorate is supporting a number of quantum-technology development efforts, such as "warm" and "cold" single-photon detectors and sources. SCaN is also supporting studies on potential applications of these technologies, from networked quantum computers to quantum-enhanced sensing of gravitational and magnetic fields.
- The Cold Atom Laboratory (CAL) on the ISS continues to expand its operational capabilities. In two experiments utilizing CAL, researchers formed condensates in thin, quasi two-dimensional bubbles, which is only possible in micro-gravity.[110]
- NASA Ames's Quantum Artificial Intelligence Laboratory (QuAIL) is part of SQMS and C$^2$QA, two of the DOE National QIS Research Centers. QuAIL contributes its expertise in quantum algorithms and tools to support quantum information processing, such as error mitigation, compilation, classical simulation of quantum systems, including high-performance computing approaches, quantum device characterization and error modeling, and benchmarking of quantum devices and algorithms. NASA's QuAIL collaborated with industry to host education outreach events in California and Colorado.

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[109] https://www.nasa.gov/directorates/spacetech/strg/stri

[110] https://www.nasa.gov/feature/jpl/ultracold-bubbles-on-space-station-open-new-paths-for-quantum-research

## 3.6 The National Security Agency (NSA)

NSA's LPS has sponsored research on quantum computing and enabling technologies since the 1990s. LPS funds domestic and international extramural research, including a broad array of QIST R&D, both directly and in partnership with ARO.[111] LPS also supports a robust internal research program at its University of Maryland, College Park facility. The LPS Qubit Collaboratory (LQC) is a QIS Research Center that enables strong interactions between government, industry, and academia across the Nation. LPS initiated a Qubits for Computing Foundry that produces qubits for the broader community. In addition, NSA, in its cybersecurity capacity, is charged with several key roles in defending National Security Systems from the risks posed by quantum computing.

**LPS QIS R&D activity highlights:**

- LPS quantum computing research programs include: the High Performance Superconducting Qubit Systems (HiPS) program; the Qubits in Silicon (QiS) program; the Stable High Fidelity Trapped Ion Systems (SHiFT) program; the Quantum Characterization of Intermediate-Scale Systems (QCISS) program;[112] the New & Emerging Qubit Science & Technology (NEQST) program;[113] and the Cross-Quantum Technology Systems (CQTS) program.[114]
- LPS, in partnership with ARO, solicited proposals through a broad agency announcement (BAA) in four research topic areas for its gate-based Quantum Computing in the Solid State with Spin and Superconducting qubit Systems (QC-S5) program.[115,116,117]
- LPS, in partnership with ARO, has an open BAA supporting the LQC for collaborative research in disruptive qubit technologies and advancing quantum learning.[118]

**Box 3.6**

**Qubits for Computing Foundry (QCF):** The LPS/ARO Qubit Collaboratory (LQC) initialized the QCF, which will remove fabrication barriers for the broader research community by providing state-of-the-art qubits, thereby enabling groundbreaking research. The QCF currently involves two seedling efforts: the MIT Lincoln Laboratory (MIT-LL) for superconducting qubits and HRL Laboratories for silicon quantum dot qubits. During these seedling efforts, the QCF will optimize the user-foundry interaction, exercise the device delivery and feedback process, and capture insight into improving future capabilities. MIT-LL has now delivered high performance qubits to eight user groups, and begun fabricating a second round of user-designed devices. These devices are being incorporated into a diverse set of research efforts, and positively impacting projects funded both by LPS and ARO, but also other Government agencies, along with some privately funded research projects. The HRL project will begin as a two-year seedling effort with the aim of providing the Government and up to two academic users with devices.

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[111] http://www.lps.umd.edu/solid-state-quantum-physics/index.html
[112] https://beta.sam.gov/opp/4e2a92e50c67472785de05973051463a/view?index=opp&page=4
[113] https://www.quantum.gov/aro-and-lps-release-baa-for-nextneqst/
[114] https://www.qubitcollaboratory.org/about/lps-solid-state-and-quantum-physics-programs/
[115] https://www.grants.gov/web/grants/search-grants.html?keywords=W911NF
[116] https://sam.gov/opp/beed50bfc65e46988f6c505b9add004e/view
[117] https://www.arl.army.mil/business/broad-agency-announcements
[118] https://www.arl.army.mil/wp-content/uploads/2021/04/LQC-BAA-Final-V8.pdf

## 3.7 The Intelligence Advanced Research Projects Activity (IARPA)

IARPA sponsors high-risk, high-payoff R&D to deliver innovative technologies to the IC and Federal Government. Over the last decade, these efforts involved several research programs in quantum computing, with recent and ongoing programs on Quantum Enhanced Optimization (QEO) for quantum annealing,[119] Logical Qubits (LogiQ) for development and demonstration of error-corrected logical qubits,[120] and the newly announced Entangled Logical Qubits (ELQ).[121]

### IARPA QIS R&D activity highlights:

- IARPA's LogiQ program has demonstrated fault-tolerant operation of four different error-corrected logical qubits, one for each of its four distinct hardware platforms based on (1) trapped-ion hyperfine qubits, (2) trapped-ion optical-transition qubits, (3) flux-tunable transmon qubits, and (4) fixed-frequency transmon qubits.

**Box 3.7**

### Highlight: Quantum Error Correction

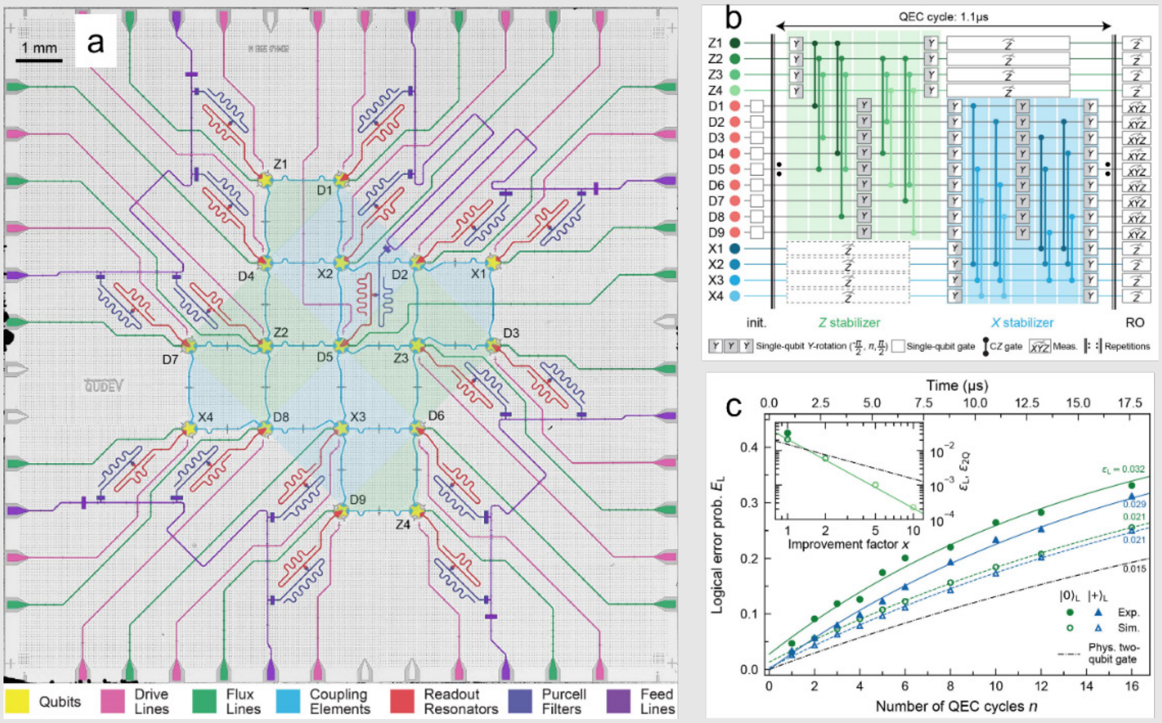

*Figure 3.5: Fault tolerant operation of a logical qubit. a) false-color micrograph of the device realizing the surface code with seventeen transmon qubits; b) quantum circuit used to initialize and (repeatedly) run quantum error correction cycles on the logical qubit; and c) logical error probability $E_L$ as a function of the number n of error-correction cycles for logical cardinal states $|0\rangle_L$ and $|+\rangle_L$.*[122]

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[119] https://www.iarpa.gov/research-programs/qeo

[120] https://www.iarpa.gov/research-programs/logiq

[121] https://www.iarpa.gov/research-programs/elq

[122] Images reproduced with permission from 'Realizing repeated quantum error correction in a distance-three surface code,' doi:10.1038/s41586-022-04566-8

Future large-scale universal quantum computers are expected to implement quantum error correction (QEC), a method that counters inevitable mechanisms of noise by collecting and redundantly encoding qubits into QEC codes, ultimately building a construct called a logical qubit. While logical qubits enable the identification and correction of errors, the redundant encoding results in significant hardware overhead and added system complexity. For logical qubits to be effective, this additional complexity must be specially designed and implemented to prevent instances of errors from dispersing and multiplying uncontrollably, a property called fault-tolerance.

Under the IARPA LogiQ program, the Quantum Device Lab at ETH-Zürich demonstrated fault-tolerant operation of a logical qubit. The team uses flux-tunable superconducting transmon qubits, which are circuit-based, planar qubits microfabricated on silicon. The mean physical coherence time of all seventeen qubits is 37.5 µs, the single-qubit gates have a mean error of 0.09% (4%), and the two-qubit gates have an average gate error of 1.5% (1.0%), with a best (worst) gate error of 0.6% (5.4%). These values are near the state-of-the-art for a system at scale.

Additionally, for qubit control instrumentation, an industry partner collaborated closely with the ETH team under the LogiQ program to develop highly integrated, low-latency qubit control modules for fast, high-fidelity qubit control and read out. This result is particularly important for a deep quantum circuit with frequent mid-circuit qubit measurements and reset operations customary to QEC circuits.

By integrating the building blocks of the logical qubit system, the team achieved 1.1 µs for each QEC cycle with a relatively low logical-qubit error rate of approximately 3% per cycle, marking the fastest QEC cycle ever performed. This development highlights significant advances in engineering of the quantum device and its operational harmony with control instrumentation and other customized apparatus and infrastructure. Moreover, the team conducted up to sixteen consecutive QEC cycles, the highest number to-date, before noise overcame and randomized the ensemble. These breakthrough achievements improve our understanding of QEC and fault-tolerance for the long-term goal of universal quantum computing.

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

# 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 key 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.

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

*Product of the*
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
*under the*
COMMITTEE ON SCIENCE
*of the*
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

SCIENCE
WORKFORCE
INDUSTRY
INFRASTRUCTURE
SECURITY
INTERNATIONAL

*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.[123] 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,[124] 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

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

[124] 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:

- The SCQIS coordinates QIS R&D across relevant agencies by sharing information and developing policy recommendations. The SCQIS has routine discussions, convenes events, and forms Interagency Working Groups (IWG) for various topics. The SCQIS, with support from the NQCO, launched the website [www.quantum.gov](https://www.quantum.gov) to help coordinate and showcase NQI activities.[125]
- Quantum sensing technologies have already been hugely beneficial to society, for example, with GPS and MRI. There are near-term opportunities for new quantum sensors to become fieldable technologies, with similarly transformative impacts; however, several challenges must be overcome to transition QIST-based sensors from the lab to market and into various mission spaces. The NSTC Subcommittee on QIS Joint IWG Quantum Sensing Activity produced a report on [Bringing Quantum Sensors to Fruition](https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf) making four policy recommendations to address these challenges: [126]
    1. Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.
    2. Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.
    3. Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.
    4. Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.

  This strategy built upon discussions that engaged agencies actively engaging in QIST R&D, like NIST, NSF, DOE, DOD, and NASA, with potential end users in agencies such as NIH, DHS, USDA, NOAA, NASA, DOD, and USGS, which may eventually apply this R&D to their mission spaces.
- The SCQIS Science IWG and NQCO convened the fourth annual QIS Program Day, bringing together QIS program managers, researchers, and stakeholders from across the Government to discuss projects and directions for QIS R&D.
- As described in its budget request to Congress, "NSF will maintain significant investment in the underlying disciplinary programs and will consider supporting new collaborative center-level activities in all areas that have the potential to enable these scientific breakthroughs."[127] Many research efforts supported by the core programs, as well as crosscutting NSF investments in QIS, address fundamental science and engineering challenges at the cutting-edge of QIS engineering research.
- IARPA explores and values the scientific approach towards universal fault-tolerant quantum computing by investing in the underlying fundamentals of quantum error correction and fault-tolerance through programs emphasizing their co-development by theory and experiment.

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[125] https://www.quantum.gov

[126] https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf

[127] https://www.nsf.gov/about/budget/fy2023/pdf/fy2023budget.pdf

**Box 4.1**

**The Quantum Networking Interagency Working Group (QN-IWG)**: Entanglement generation and distribution, and the supporting quantum networking R&D, connects with the missions of several agencies. A Coordinated Approach to Quantum Networking Research is essential to leveraging the unique capabilities, missions, and funding models of these agencies.[128] With vast parameter and mission spaces, no one agency can solve all of the problems. Fifteen agencies are represented in the QN-IWG, including AFOSR, AFRL, ARL, ARO, DARPA, DOE, LTS, NASA, NIST, NRL, NRO, NSA, NSF, ONR, and OSTP. This IWG provides a forum for interagency dialogue prior to program announcements, workshops, and meetings, and to communicate progress and priorities.

A whole-of-government approach leverages investments from both core and center-scale programs, with a balance of R&D efforts spanning applications, components, testbeds, and supporting technology for quantum networks. A partial list of recent efforts includes:

- DOE awarded projects in entanglement distribution, and two quantum internet regional-scale testbed projects, consistent with the CHIPS and Science Act of 2022.
- NSF issued ten grants totaling $25 million for work on Quantum Interconnect Challenges under the QuIC-TAQS program.
- ARO funded two MURIs focusing on distributed entanglement totaling $2.5 million per year.
- NIST, in conjunction with JILA and the NSF QLCI Q-SEnSE, has research efforts dedicated to transduction, repeaters, and readout.
- DARPA held the Quantum-Classical Networking Interoperability Workshop, which was coordinated within the QN-IWG and had extensive participation from IWG membership.

Quantum networking testbeds across the United States are enabling new experiments and use-case development, cross-cutting component development, and classical support systems, including:

- The NSF QLCI on Hybrid Quantum Architectures and Networks in Illinois and Wisconsin.
- The Chicago Area Quantum Network, including Argonne National Laboratory and QNext.
- NRO completed an architecture study of the Multi-node Testbed for Space-based Long-distance Teleportation, which is intended to interconnect distributed local area quantum networks, fostering interagency collaborations, while advancing a vital capability for the National Security Space.
- The NSF-funded Center for Quantum Networks headquartered in Arizona.
- The AFRL Information Directorate Distributed Quantum Networking Testbed explores entanglement distribution across heterogeneous qubit technologies spanning basic and applied research.
- DC-QNet, based in Washington D.C., provides a coordinated multi-agency fiber-based testbed connecting six agencies across the metropolitan area.
- NASA and NIST are collaborating to develop an advanced quantum metrology capability at NASA's Glenn Research Center which will impact quantum networking technologies.
- NASA and NRO are collaborating on QIS technology development and demonstrations addressing future space-based quantum networking capabilities.

This list is not intended to be comprehensive, but rather illustrates some of the range of activities and span of agencies engaged.

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[128] https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf

- NSF-funded workshops provide input from R&D leaders in deliberative forums to guide ongoing research that continues to explore QIS frontiers.[129- 136]
- The DHS S&T Directorate established a QIST Community of Interest (COI) to provide awareness into the state of QIST R&D activities. The DHS QIST COI brings representatives from components at DHS, the Federal Government, and research organizations together with the DHS community of potential users spanning QIST topic areas, including matters related to encryption and PQC.
- The National Institutes of Health (NIH) established a trans-NIH Working Group on QIS with representatives from over 12 NIH institutes and experts from DOE, NIST, and NSF to discuss joint opportunities in the areas of quantum sensing and quantum computing. The goal of this working group is to identify biomedical problems that may be amenable to quantum information/sensing applications, such as the measurement of highly sensitive and specific biological and cellular signals in normal and diseased states. NIH also established a Quantum Sensing Scientific Interest Group (SIG),[137] to promote knowledge sharing in QIS and to provide resource for NIH intramural scientists, fellows, graduate students, and interns.
- NIH, DOE, NIST, NSF, and DARPA participated in a multi-agency meeting on Quantum Information Technology Applications in Biomedical Sciences aiming to explore how current and future applications of quantum-enabled technologies, specifically quantum sensing technologies, can lead to new insights in biomedical sciences.
- A call for proposals for a second series of investigations on the CAL facility was released in June. NASA is broadening the science base of its cold atom project with this proposal call, requesting proposals for ground-based research to identify new objectives for future space experiments.[138]
- NRL, ARL, USNO, NIST, NSA, NASA, and affiliate members consisting of the Naval Information Warfare Center-Pacific and AFRL, announced the formal establishment of the DC-QNet. DC-QNet is developing the network infrastructure for connecting the six metropolitan agencies via a dark-fiber network to perform entanglement distribution at kilometer distances, in addition to developing high-fidelity quantum memory nodes, single-photon devices, network metrology, qubit platforms, transduction and frequency conversion, synchronization, and development of the enabling science and technology including emulation, modeling and simulation of quantum networks, R&D into classical interfaces, routing, monitoring and metrology, and associated quantum network software.[139]

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[129] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2139007

[130] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2138059

[131] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2138437

[132] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2212755

[133] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2204700

[134] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2204700

[135] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2202377

[136] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2230199

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

[138] https://science.nasa.gov/researchers/solicitations/roses-2022/amendment-25-final-text-and-due-dates-e6-fundamental-physics

[139] https://www.nrl.navy.mil/Media/News/Article/3060477/nrl-announces-the-washington-metropolitan-quantum-network-research-consortium-d/

## 4.2 Creating a Quantum-Smart Workforce for Tomorrow

The United States has built a strong foundation for QIS R&D over the past several decades, with a baseline level of research infrastructure and a scientific and technical workforce comprising talented college graduates, PhD students, postdocs, staff scientists, and professors. The workforce has grown through the steady process of funding fundamental research and through job opportunities at universities, Federal laboratories, and quantum-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 United States Government, the SCQIS released a QIST Workforce Development National Strategic Plan.[140] 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**

- NSF and the NQCO, in coordination with the Q-12 partnership, co-hosted a "Quantum Workforce: Q-12 Actions for Community Growth" virtual roundtable. The NQCO and NSF were joined by professors, high school teachers, industry partners, and experts in education, diversity, equity, and inclusion for a number of unique sessions aimed at exploring specific actions needed to ensure progress in early quantum education. During the meeting, the SCQIS released the aforementioned QIST Workforce Development National Strategic Plan.
- During the "Pursuing Quantum Information Together: $2^N$ vs 2N" meeting, a roundtable discussed international quantum workforce needs. In addition to this, the NQCO engaged in several country-to-country dialogues that included workforce as a topic of focus.

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

To engage more people, earlier:

- The NSF-supported Q2Work program, as part of the Q-12 Education Partnership, worked with high school teachers from physics, computer science, chemistry, and mathematics to develop K-12 frameworks based on the Key Concepts for Future Quantum Information Science Learners identified in 2020.[141]

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[140] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf
[141] https://qis-learners.research.illinois.edu/about/

**Box 4.2**

### Federal Engagement in World Quantum Day

*Figure 4.2: A public domain graphic produced by Federal agencies to promote World Quantum Day.*

The NQCO helped facilitate U.S. engagement in World Quantum Day held on April 14, 2022. World Quantum Day is an international, community-driven annual event to spark interest and generate enthusiasm for quantum mechanics.[142] The coordinated efforts of several agencies produced a wide range of content that highlights both quantum science and the people working in the field.

Videos and Social Media:

- The Q-12 Education Partnership, through NSF support, produced a video titled "This Is Quantum" that conveys an inclusive message of engagement in quantum science.[143] The video was released by OSTP, NSF, and NASA and has been viewed over 100,000 times.
- Federal agencies were active on social media and released a range of content,[144] with a particular focus on highlighting a diverse group of Federal scientists working in the field. These videos have also received tens of thousands of views. Altogether, social media posts generated by U.S. Government entities reached over 6 million people.
- For World Quantum Day, the Q-12 Educational Partnership launched the QuanTime program to bring quantum lessons into roughly five hundred K-12 classrooms, engaging thousands of students in an activity based in quantum science.[145]
- Agencies curated images of federally-funded quantum research to post on a quantum image gallery on quantum.gov; the images are free for reuse with appropriate citations.[146]
- NIST created an infographic explaining Planck's constant, an important number for which the date for World Quantum Day, April 14th, was chosen to honor.[147]
- Finally, the NQCO released a factsheet on the National Quantum Initiative.[148]

Almost all of the Federal content is curated on either quantum.gov or q12education.org, making it available for people to connect with and learn from in the coming years.

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[142] https://www.worldquantumday.org
[143] https://twitter.com/nasa/status/1514690405538877444
[144] https://www.quantum.gov/world-quantum-day/social-media-posts/
[145] https://q12education.org/quantime
[146] https://www.quantum.gov/quantum-image-gallery
[147] https://www.quantum.gov/wp-content/uploads/2022/04/PlancksConstant_Infographic_Full_Resized.png
[148] https://www.quantum.gov/wp-content/uploads/2022/04/NQI-Factsheet.pdf

- NASA SOMD is developing QuantumComm 101, an internet-based educational tool for teachers and students, introducing them to concepts, technologies, and potential applications of QIST.
- As shown in Box 4.2, many agencies participated in World Quantum Day. In the United States, federally-funded activities helped support outreach initiatives, like QuanTime, which brought short classroom learning activities to tens of thousands of students across the country.
- NASA's SOMD launched a summer faculty program to focus on QIST and STEM. For 2022, two faculty were selected to work with SOMD's Space Communications and Navigation (SCaN) to explore ways to inject QIST-related topics into curricula across all levels.[149] SOMD/SCaN is also collaborating with NASA's Office of STEM Engagement to share quantum educational materials with U.S. teachers through a recently developed app, CONNECTS, as well as with NASA's Space Grant Consortium community.
- 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, including in physics, engineering, mathematics, and computer science.
- AFOSR launched two STEM education funding opportunities, a STEM FOA and DURIP-LL, which can be used for QIS. The STEM FOA encourages projects that improve the capacity of education systems and communities to create impactful STEM educational experiences for students of all ages in the air- and space-related workforce. DURIP-LL seeks proposals from universities to create, market, and implement a lending library program using DURIP-funded instrumentation.

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

To better understand education and training needs for teaching students:

- LPS/LQC hosted a virtual Workshop on Gaps in Postsecondary Quantum Education and Training. The workshops brought together stakeholders from academia, industry, and government to discuss developing collaborations for fixing the educational and training gaps in QIS.

To provide short-term training, agencies funded short courses and summer programs:

- LPS/LQC hosted a two-week introduction to quantum computing course which covered topics ranging from algorithms to physical implementations of quantum systems. This is the second Summer of Quantum short course and is designed for rising upper-level undergraduates, and first- and second-year graduate students.
- The DOE National QIS Research Centers hosted several summer schools as introductions to QIS.
- NASA QuAIL is supporting the organization of a Summer School on Quantum Simulation of Field Theories that is being organized in collaboration with the DOE SQMS center.
- The development of competencies and skills in computational science, data science, QIS, and machine learning is an essential part of the development of the future STEM workforce. A highly successful summer school on quantum computing and the nuclear many-body problem was held at the DOE User Facility for Rare Isotope Beams (FRIB). All lectures were recorded and are accessible to the public.

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[149] https://www.quantum.gov/nasa-scan-quantum-faculty-fellowship-opportunities/

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

To help grow capacity and get more people involved:

- NSF launched the ExpandQISE program to increase research capacity and broaden participation in QISE and related disciplines at institutions that currently do not have a large QISE portfolio.[150] The ExpandQISE management team organized a series of virtual connection-building workshops, designed to facilitate contact between potential PIs and external Co-PIs on ExpandQISE proposals.
- The DOE ASCR program released a funding opportunity for its RENEW activities. The program seeks to increase participation of underrepresented groups in the quantum computing and networking workforce and to increase participation of underrepresented institutions in quantum computing and networking workforce training.

To support careers:

- LPS and the NQCO held a virtual workshop on the recruitment of individuals with QIS expertise into Government service. The workshop focused on challenges and best practices for recruiting and retaining the talent needed to ensure the Government has ample awareness of and expertise in QIS challenges and opportunities.
- The five DOE National QIS Research Centers sponsored and organized an annual career fair which had hundreds of students and postdoctoral researchers in attendance.
- LPS partnered with AFOSR to support the young investigator research program in QIS. The program supports scientists and engineers early in their career who have received a PhD, or equivalent, and have shown exceptional ability and promise for conducting basic research.
- Building the workforce of the future is part of the mission of DHS, and its S&T Directorate in particular. In FY 2021 and FY 2022, DHS S&T used a combination of direct hire, IPA, and detailees to build a new QIS team to provide expertise and lead quantum technology activities.

## 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 the industry capabilities. At the same time, the growth of new industries enables new scientific discoveries and empowers more of the Nation to benefit.

However, the successful translation of scientific discoveries to deployed technologies is challenging, often requiring 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 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.

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[150] https://www.nsf.gov/pubs/2022/nsf22561/nsf22561.htm

- As part of the NQI Act, NIST established and oversees the operation of the QED-C. NIST continues QED-C coordination with an active seat on its board and by engaging in joint R&D projects with NIST researchers, the QED-C, and its industry members.
- The new NSF TIP Directorate includes a Lab-to-Market portfolio with several programs that can promote translational research in QIS,[151] such as the Convergence Accelerator, I-Corps, America's Seed Fund powered by NSF, and the NSF Engines, all of which can support QIS activities.
- NSF mechanisms for engaging with industry also include the Grants Oriented for Academic Liaison with Industry (GOALI) program, the Industry-University Cooperative Research Centers (IUCRC) program, as well as the INTERN and Triplets programs.
- IARPA makes awards through full and open competition, engaging the best of academia and industry, such as members of the quantum-industry sector that are presently funded under the LogiQ program.
- DHS funded a study to explore the potential benefits of QIST to the agency, such as tunnel detection, both long- and short-range sensing, and optimization problems for scheduling algorithms, with each of these areas now being explored by both QIST R&D experts and those with expertise in DHS use cases. In addition, the DHS S&T Directorate coordinated with NIST on the development of a detailed description of QIST use cases and the current solutions in use by DHS, exploring whether QIST-based solutions may provide advantages to DHS mission needs.

## 4.4 Providing Critical Infrastructure

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

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

- The NSF National Nanotechnology Coordinated Infrastructure (NNCI) program supports sixteen user facility sites, their affiliated partners, and a coordinating office.[152,153] These sites provide researchers from academia, small and large companies, and the Government with access to university user facilities with cutting-edge fabrication and characterization tools,

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[151] https://beta.nsf.gov/tip/about-tip

[152] https://beta.nsf.gov/funding/opportunities/national-nanotechnology-coordinated-infrastructure-nnci

[153] https://nnci.net/

instrumentation, and expertise within all disciplines of nanoscale science, engineering, and technology. A community-led workshop was held in 2021 to enhance engagement of the NNCI network with QIST R&D.[154,155]

- NIST upgraded laboratory facilities for quantum networking projects at both of its campuses and is developing a portable optical atomic clock for improved time service. In addition, NIST is building out a service to support single and entangled photon metrology to create the foundation for quantum radiometry.
- NSF is exploring the concept of a QIS and Engineering National Virtual Laboratory (NVL), which will serve as a nation-wide, community-driven effort that supports the smooth integration and translation of fundamental science and engineering to use-inspired applications. The NVL concept is briefly described in the NSF Budget Request to Congress for FY 2023,[156] and it was further developed by a community-led project scoping workshop in June of 2022.[157]
- LPS hosts the LQC Quantum Research Center and has initiated the Qubit Foundry program.
- IARPA funds R&D to advance critical infrastructure, both hardware and software, for quantum computing that is made available to USG-funded programs in their quantum technology pursuits.
- The DOE IP advanced the construction of the U.S. Stable Isotope Production and Research Center (SIPRC) at ORNL. SIPRC will use new electromagnetic isotope separator and gas centrifuge capabilities to significantly expand domestic stable isotope production essential for QIS applications. This capability will relieve U.S. dependency on Russia for enriched stable isotopes needed for QIS and other applications.
- NASA is collaborating with NIST to develop an advanced quantum metrology capability at NASA's Glenn Research Center.

## 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.

- The FY 2022 NDAA expanded national QIST activities through:[158]
  - Codifying ESIX, along with providing specific responsibilities for the Subcommittee;
  - Supporting the development of QIST within the DOD, as well as new annual reporting requirements on DOD progress;
  - Modifying an ongoing grant program for STEM education in the Junior Reserve Officers' Training Corps to include QIST; and
  - Authorizing additional funding for quantum computing and quantum networking, along with augmenting quantum sensing, research, education, and training at HBCUs.

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[154] https://nsf.gov/awardsearch/showAward?AWD_ID=2124834&HistoricalAwards=false

[155] https://www.cnf.cornell.edu/events/nsf-nnci-quantum

[156] https://www.nsf.gov/about/budget/fy2023/pdf/fy2023budget.pdf

[157] https://nsf.gov/awardsearch/showAward?AWD_ID=2230199&HistoricalAwards=false

[158] National Defense Authorization Act for Fiscal Year 2022 (Pub. L. 117-81) §§ 229, 511, 1251 and 6606; 10 U.S.C. §§ 4001 and 2036(g)(2)(J) and 15 U.S.C. § 8814a

- IARPA maintains a robust research technology protection program that evaluates the possible implications of research objectives and outcomes to national security. While the potential economic growth a program could or would represent does not enter into decisions for research protection, researchers funded under IARPA's quantum technology programs have established U.S. startup companies in relevant fields.
- PQC, also known as quantum-resistant cryptography, includes measures such as updating cryptographic protocols and standards. As described in Box 4.3, PQC research and implementation activities are supported by several SCQIS and ESIX agencies including NIST, NSF, DOD, DHS, and NSA.

**Box 4.3**

**The National Security Memorandum – 10 (NSM-10)** promotes United States leadership in quantum computing while mitigating risks to vulnerable cryptographic systems.[159] Quantum computers have the potential to drive American innovation and economic prosperity. With the capability to efficiently solve otherwise intractable mathematics problems that underpin many public-key cryptography protocols used to secure digital systems across the world, sufficiently large and sophisticated quantum computers also pose risks to the economic and national security of the United States.

To ensure a vibrant, fair, and competitive market that nurtures scientific and economic opportunities, the United States must maintain leadership in QIS through continued investments and partnerships, and mitigate the threat of cryptanalytically relevant quantum computers through a timely and equitable transition to quantum-resistant cryptography.

A whole-of-government and whole-of-society strategy will balance these opportunities and risks, encouraging transformative and fundamental scientific discoveries, while providing the security enhancements of quantum-resistant cryptography. Building the next generation of scientists will be critical to ensuring that the United States has the necessary talent to remain at the forefront of QIS and effectively update and protect vulnerable cryptosystems.

- NIST leads a broad effort to develop PQC standards, enabling encryption that is secure against attack by both classical and quantum computers, which can interoperate with existing communications protocols and networks. In addition, the QED-C has a "Quantum for National Security" Technical Advisory Committee that is focused on the supply chain for national security applications of QIS.
- In October 2021, DHS released a PQC transition roadmap to provide actionable recommendations to DHS's critical infrastructure and its state, local, tribal, and territorial (SLTT) partners.[160] In line with NSM-10, DHS continues to engage on PQC with industry, critical infrastructure providers, and SLTT partners to promote the need for transition planning.
- NSA acting as the National Manager for National Security Systems has begun collecting data on National Security Systems to prioritize upgrades related to PQC.

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[159] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/

[160] https://www.dhs.gov/quantum

- NSA does not recommend the use of quantum key distribution and quantum cryptography for securing the transmission of data in National Security Systems unless certain limitations are overcome.[161]
- NSA emphasized the importance of PQC (see Box 4.1) and updated its cryptographic algorithms suite (CNSA 2.0)[162,163] to adopt post-quantum cryptography algorithms now that NIST has announced its Round 3 selections.
- DOE IP invests in technology development for the enrichment and production of isotopes critical to QIS R&D, reducing the Nation's dependence on foreign resources for QIS applications of importance to national security.

## 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, facilitate communication, and demonstrate shared principles through the conduct of research and education. QIS R&D is deeply international, with talent, infrastructure, and industrial capabilities globally diffused. As of 2022, about three dozen countries around have significant government funding for QIS research, and at least 17 have national strategies for quantum technology development.[164] 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.[165] 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 a number of mechanisms. For instance, bilateral agreements between U.S. agencies and their international counterparts enable benefits such as a coordinated review process, reciprocal or joint funding, and student and researcher exchange to the benefit of both parties. Some agencies, pursuant to their mission and authorities, can also pursue unilateral support for international research collaborators. Informal engagements with universities and industry are also essential to connect government, academic, and private sector stakeholders. Through these collective approaches, a large number of federally-funded QIS research projects and initiatives continue to enjoy international collaborators, resulting in coordinated efforts with mutual benefits.

- The SCQIS, ESIX, and OSTP coordinate with the Department of State (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 Statements of Cooperation on QIST with Australia, Denmark, Finland, Sweden, and the United Kingdom; these statements are in addition to the one signed with Japan in 2019. Each of these bilateral statements highlight the United States' commitment to building a vibrant international quantum ecosystem by embarking on

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[161] https://www.quantum.gov/nsa-cybersecurity-perspectives-on-quantum-key-distribution-and-quantum-cryptography/

[162] https://www.nsa.gov/Press-Room/News-Highlights/Article/Article/3148990/nsa-releases-future-quantum-resistant-qr-algorithm-requirements-for-national-se/

[163] https://media.defense.gov/2022/Sep/07/2003071747/-1/-1/0/CSA_CNSA_2.0_ALGORITHMS.PDF

[164] https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf

[165] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

good-faith cooperation that is underpinned by our shared principles including openness, transparency, honesty, equity, fair competition, objectivity, and democratic values.

- U.S. international QIS activities are distributed across several agencies, each pursuing QIS mission-specific collaborations, unilaterally with agency partners.
    - On December 6-7, 2021, DOS hosted the sixth U.S.–France Joint Committee Meeting (JCM) on S&T Cooperation, convening technical and policy experts from both countries to discuss S&T matters of mutual importance. The U.S.–France JCM featured an Emerging Technology: Quantum Information Science roundtable.
    - DOS leveraged its Embassy Science Fellowship Program to send U.S. Government technical experts to Denmark, Finland, Germany, the Netherlands, Sweden, and Switzerland to learn more about these countries' respective QIS ecosystems, develop relationships, further agency objectives with these partners, and identify opportunities for deeper collaboration.
    - DOS and the NQCO organized a June 28, 2022 QIS workshop with the Republic of Korea, convening university, national laboratory, and government technical experts to discuss respective QIS research trends and identify areas for future cooperation.
    - Consistent with the July 2021 Joint Statement of Principles in Support of International Education, DOS announced additional measures to further support for increasing the flow of STEM talent, including in QIS. The Early Career STEM Research Initiative seeks to connect BridgeUSA exchange sponsors with interested U.S.-based STEM host organizations (e.g., small- and medium-sized businesses). DOS also announced an extension for undergraduate and graduate students in STEM fields on the J-1 visa that will facilitate additional academic training for periods of up to 36 months.

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

- DHS S&T Directorate engaged with NATO to discuss joint interests and collaboration opportunities in QIST. In addition to identifying several QIS areas of mutual interest, both the DHS S&T Directorate and NATO plan to hold a series of workshops in 2022 and 2023 on QIST use cases with the goal of furthering this collaboration and identifying quantum technology solutions to existing problems.
- IARPA's quantum computing 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.
- NASA Ames Research Center and the German Aerospace Center (DLR) signed a three-year agreement in January 2022 intended to advance their respective quantum computing research thrusts. The focus of the agreement is on jointly developing a software library composed of software tools to implement quantum algorithms with space exploration applications.[166]
- A NASA-SOMD team supported a July 21-22 workshop in Canberra, Australia sponsored by Australia's National Science Agency (CSIRO), with a focus on potential cooperation in space-based quantum communications, which would parallel current cooperation in optical communications between NASA and various Australian agencies and universities.

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[166] https://www.dlr.de/content/en/articles/news/2022/01/20220303_dlr-and-nasa-developing-software-package-for-quantum-computers.html

- Under the Australia-United Kingdom-United States (AUKUS) Partnership, the Quantum Science Working Group and the AUKUS Quantum Arrangement will accelerate investments to deliver next-generation quantum capabilities. These efforts are initially focused on QIST-based PNT, and together, over the next three years, the countries will integrate emerging quantum technologies in trials and experimentation.[167]

**Box 4.4**

### International Roundtable on Pursuing Quantum Information Together: $2^N$ vs 2N

*Figure 4.3: The participants, from twelve countries, that attended the QIS roundtable.*

Building on its bilateral engagements, OSTP and DOS hosted an international QIS roundtable on May 5-6.[168] The roundtable gathered the leaders of quantum strategy offices from the United States, Australia, Canada, Denmark, Finland, France, Germany, Japan, the Netherlands, Sweden, Switzerland, and the United Kingdom, reinforcing the importance of international cooperation in QIST to accelerate discovery, share resources, and jointly address global challenges. On day one, the dialogue focused on opportunities for next steps toward growing international cooperation in these areas. Examples include highlighting exchange opportunities for students, postdocs, and professionals, and improving awareness through the promotion of events like World Quantum Day. For day two, the countries discussed how to shape a healthy, global QIST ecosystem.

*About the meeting title: As the number of qubits (which are the fundamental building blocks of a quantum computer) doubles in size, a property called quantum entanglement enhances the power of quantum information processing. “$2^N$ vs. 2N” refers to this exponential increase in performance when qubits are entangled. We strive in collaborations to create a whole that is more than the sum of its parts. Accordingly, the theme for this meeting was to continue prior discussions beyond one-to-one conversations and set the stage for continuing multi-country engagements.*

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[167] https://www.whitehouse.gov/briefing-room/statements-releases/2022/04/05/fact-sheet-implementation-of-the-australia-united-kingdom-united-states-partnership-aukus/

[168] https://www.whitehouse.gov/ostp/news-updates/2022/05/07/readout-international-roundtable-on-pursuing-quantum-information-together-2n-vs-2n/

## 5 Summary and Outlook

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

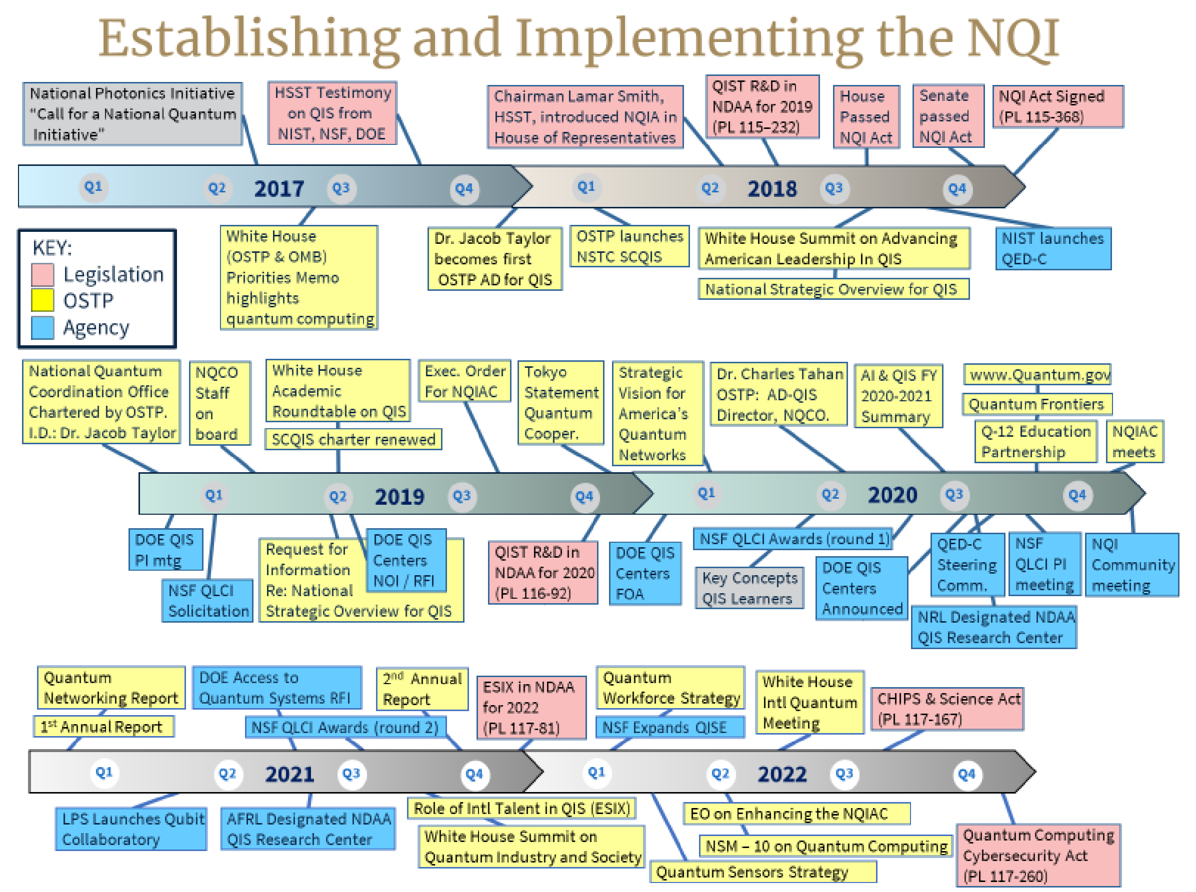

*Figure 5.1: Timeline of actions establishing and implementing the NQI. Color-coding shows legislative process in red; OSTP and NSTC actions in yellow; agency actions in blue. The NQI was introduced in Congress, passed in the House, passed in the Senate, and signed into law by the President, reflecting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

The NQI Act calls for a ten-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.