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

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The NSTC Subcommittee on Quantum Information Science (SCQIS) coordinates Federal research and development (R&D) in quantum information science and related technologies under the auspices of the NSTC's Committee on Science. This coordinated R&D aims to ensure that U.S. leadership in quantum information science and its applications is maintained and expanded over the next decade.

Acknowledgments

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Acronyms

USDA	Department of Agriculture
DOD	Department of Defense
DOE	Department of Energy
NIH	National Institutes of Health
DOI	Department of the Interior
DHS	Department of Homeland Security
State	Department of State
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSA	National Security Agency
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
QIS	Quantum Information Science
NSTC	National Science and Technology Council
SCQIS	NSTC Subcommittee on Quantum Information Science

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1 Quantum information science: the next technological revolution

Quantum information science (QIS) applies the best understanding of the sub-atomic world—quantum theory—to generate new knowledge and technologies. Through developments in QIS, the United States can improve its industrial base, create jobs, and provide economic and national security benefits. Prior examples of QIS-related technologies include semiconductor microelectronics, photonics, the global positioning system (GPS), and magnetic resonance imaging (MRI). These underpin significant parts of the national economic and defense infrastructure. Future scientific and technological discoveries from QIS may be even more impactful. Long-running U.S. Government investments in QIS and more recent industry involvement have transformed this scientific field into a nascent pillar of the American research and development enterprise. The Trump administration is committed to maintaining and expanding American leadership in QIS to enable future long-term benefits from, and protection of, the science and technology created through this research. Based on the collective input of all the Government agencies invested or interested in QIS, this document presents a national strategic approach to achieving this goal.

Specifically, the United States will create a visible, systematic, national approach to quantum information research and development, organized under a single brand and coordinated by the National Science and Technology Council's (NSTC) Subcommittee on Quantum Information Science (SCQIS). These efforts will leverage existing programs and approaches, adapt to the changing and improving scientific and technical knowledge, reflect the best understanding of opportunities and challenges in QIS for the Nation, and take new steps where appropriate. The national effort will:

- Focus on a science-first approach that aims to identify and solve Grand Challenges: problems whose solutions enable transformative scientific and industrial progress;
- Build a quantum-smart and diverse workforce to meet the needs of a growing field;
- Encourage industry engagement, providing appropriate mechanisms for public-private partnerships;
- Provide the key infrastructure and support needed to realize the scientific and technological opportunities;
- Drive economic growth;
- Maintain national security; and
- Continue to develop international collaboration and cooperation.

The key next step will be to develop agency-level plans that address the identified approaches and policy opportunities in the next section, which will be integrated into an overall strategic plan. This will enable new opportunities on a ten-year horizon, possibly including: the development of quantum processors which may enable limited computing applications; new sensors for biotechnology and defense; next-generation positioning, navigation, and timing systems for military and commercial applications; new approaches to understanding materials, chemistry, and even gravity through quantum information theory; novel algorithms for machine learning and optimization; and transformative cyber security systems including quantum-resistant cryptography in response to developments in QIS.

2 Summary of key policy opportunities

The policy opportunities identified in this strategic overview are summarized below. Following these recommendations, along with detailed planning and coordination made possible by the SCQIS as well as engagement with stakeholders, is crucial for the United States' future success.

Choosing a science-first approach to QIS

- Strengthen Federally-funded core research programs and use approaches ranging from distributed small grants to centers and consortia where appropriate, to support long-term QIS research
- Foster dialogue and collaboration between quantum-focused researchers across disciplines, and engage the broader scientific community to highlight and share relevant scientific advances, and grow and coordinate the quantum research community
- Establish and utilize a formal coordination body, such as the National Science and Technology Council Subcommittee on Quantum Information Science (SCQIS)
- Focus on Grand Challenges as a mechanism for driving advancements in the science and technology of QIS, and encourage Federal agencies to identify, prioritize, and coordinate investment in both fundamental and applied challenges

Creating a quantum-smart workforce for tomorrow

- Encourage industry and academia to create convergent, trans-sector approaches for diverse workforce development to meet the Nation's QIS needs
- Use and enhance existing programs to increase the size of the QIS-ready workforce
- Encourage academia to consider quantum science and engineering as its own discipline, with needs for new faculty, programs, and initiatives at all levels
- Address education in the area of quantum science at an early stage, including elementary, middle and high school levels
- Reach out to broader audiences by working with involved agencies and industry to highlight their investments, along with novel or unconventional approaches like utilizing art, media, and engagement with cultural institutions
- Encourage the QIS community to track and estimate the future workforce needs of quantum industry

Deepening engagement with quantum industry

- Foster the formation of a U.S. Quantum Consortium with participants from industry, academia, and Government to forecast and establish consensus on needs and roadblocks, coordinate efforts in pre-competitive research, address intellectual property concerns, and streamline technology-transfer mechanisms
- Increase investment in joint quantum technology research centers by partnerships between industry, academia, and Government to accelerate pre-competitive quantum research and development
- Maintain awareness of how the quantum revolution may effect agency mission spaces and how agencies can nurture the adoption of quantum technologies within the Federal Government by cultivating potential end-user application spaces

Providing critical infrastructure

- Identify critically needed infrastructure and encourage necessary investments by working with Government experts and stakeholders, as well as industry and academia.
- Encourage agencies to provide the QIS research community with increased access to existing and future facilities and supporting technologies
- Establish end-user testbed facilities along with training and engagement, thereby allowing Federal agencies and stakeholders to explore applications relevant to their respective missions
- Leverage existing infrastructure, including manufacturing facilities that can be repurposed and expanded, to rapidly advance quantum technology development

Maintaining national security and economic growth

- Maintain an understanding of the security implications of the changing science and technology landscape in QIS
- Promote mechanisms, such as the SCQIS, for all Government agencies to stay abreast of the defense and security implications of QIS technologies and help balance the benefits of economic growth with new risks created by the technology
- Ensure consistent application of existing classification and export control mechanisms to provide the largest amount of information possible to American universities and industry about actions related to QIS research to encourage economic opportunities, protect intellectual property, and defend national-security-relevant applications.

Advancing international cooperation

- Seek to increase international cooperation with like-minded industry and Government partners
- Ensure the United States continues to attract and retain the best talent, and has access to international technologies, research facilities, and expertise in QIS
- Identify strengths and focus areas, as well as gaps and opportunities, of international actors to better understand the evolving international QIS landscape from both technical and policy perspectives.

Next steps

Government agencies have been asked to create detailed execution plans in support of these policy goals and informed by these policy options. Specifically,

1. Agencies participating in the SCQIS shall provide written plans for addressing the policy goals outlined here by the first quarter of 2019, or a later date as arranged with OSTP and the SCQIS.

2. Consistent with law, agencies shall convene stakeholders in consultation with OSTP and the SCQIS to identify Grand Challenges in specific sub-fields, such as: quantum accurate sensors, quantum sensing technology, applications of quantum networks, development of quantum-resistant cryptographic standards and systems, commercial possibilities for NISQ quantum devices, approaching the high-fidelity limit of qubit operation, and foundational new science from QIS.

3 Challenges this strategic overview addresses

The rapid growth of QIS and the expectation that this trajectory will continue over the next decade create unique opportunities and challenges for the U.S. research and development enterprise. Underscoring the Trump Administration's commitment to advancing QIS, the NSTC elevated its work on the subject and established the SCQIS, which has identified four key challenges that need to be addressed with a whole-of-Government response.

First, improving and facilitating **coordination** both within the Government and between public and private institutions will create a robust domestic ecosystem and provide worldwide leadership in this international environment. The Nation already has strong and diverse programs in QIS at the Federal-agency level driven by individual mission spaces, as described in the Appendix. Similarly, companies have begun making major investments in the field, inspired by the promise of future applications. At the same time, foreign countries are making investments and seeking to build their own QIS base in competition with the United States. Coordinating U.S. efforts will take advantage of the Government and industry activities to maintain and accelerate U.S. leadership in QIS.

Second, growth within industry, academia, and Government requires maintaining and expanding a broad and viable **workforce**—a quantum-smart workforce—able to enact critical elements of the research and development enterprise. Such a workforce will attract and retain key jobs throughout the Nation, and enable new industrial and academic efforts that rely upon QIS as a base technology.

Third, future progress in QIS requires strong **cross-community connections** between disciplines, from physics to computer science to engineering. These interactions already occur through research collaborations, but would benefit further from formal interdisciplinary research and training programs at earlier levels of education. As growth continues, collaborations and cooperation—between disciplines and nations, between industry and academia—must be promoted, even as competitive pressures may make this more difficult.

Fourth, significant uncertainty remains regarding the overall economic and national security impact of QIS research and development. With strong industrial engagement now beginning, it is crucial to maintain a culture of **discovery**. The likely best-use commercial cases of quantum devices are *unknown at this time* and must be found through research. Maintaining this focus, despite significant countervailing pressures, is necessary. The technologies that are anticipated to result from this approach may also play a role in solutions to some of the Nation's most pressing national security concerns, but will require maintaining an understanding of national security implications of QIS.

In order to maintain and expand American leadership in this critical technology given these challenges, we must improve our capacity for cutting edge research and development, expand the QIS-literate workforce, and seamlessly coordinate between government, academic, and private sector players.

4 Choosing a science-first approach to QIS

Quantum information science—including concepts and technology that support revolutionary advances in computing, communications, and metrology—arises from a synthesis of quantum mechanics and information theory. It examines uniquely quantum phenomena that can be harnessed to advance information processing, transmission, measurement, and fundamental understanding in ways that classical approaches can only do much less efficiently, or not at all. Current and future QIS applications differ from prior applications of quantum mechanics, such as the laser, transistor and MRI, by using distinct quantum phenomena—superposition and entanglement—that do not have classical counterparts.

Even though its origins can be traced back to the 1960's, QIS remains a rapidly evolving scientific and engineering discipline with substantial further discovery opportunities awaiting. This reflects the Government's long support of basic research and development in this field. Even now, while prototype QIS applications, platforms and devices are becoming commercially available, new applications and platforms will likely come from protocols and approaches that are not yet invented. **Thus, the Government should maintain robust and diverse platforms and research thrusts that continue to stimulate transformative and fundamental scientific discoveries by taking an approach that puts the science first.** This will require strengthening core research programs and finding new methods to broaden collaboration and participation.

To capitalize on QIS-inspired technologies and advance the science necessary to realize the associated gains, the development and pursuit of scientific and applied Grand Challenges will be the unifying strategy. Grand Challenges are those fundamental scientific or technology problems with answers that will be transformative for Nation and have broad economic and scientific impact. Potential solutions will take sustained investments for at least ten years and require multidisciplinary teams of researchers and technologists. Agencies, academia, and industry must work together to identify and prioritize Grand Challenges, as well as track their progress and reevaluate these scientific and technological opportunities as the research and development progress.

Solving Grand Challenges and realizing the potential of QIS will depend on employing effective models of coordination and collaboration to tap the unique skills and perspectives from Federal agencies, industry, and academia, and to create and maintain a dialogue between quantum-focused researchers across disciplines. Towards this end, centers and consortia can be a powerful means of gathering and maintaining research communities that can sustain such long-term, curiosity-driven research. In addition, the SCQIS's coordination role as well as mechanisms such as professional science and engineering society participation, coordinated Principal Investigator meetings, and dissemination of information through scientific journals, will help to highlight and share quantum scientific advances and to grow the quantum research community.

Grand Challenge opportunities

Quantum approaches motivated by Grand Challenges show promise for providing new capabilities and tools for sensing and metrology, communication, simulation, and computation. This is vital for fundamental research and promotes security, health, and the economy. For example, quantum sensing holds the promise to provide advanced sensors for military mission impact, to develop new measurement science and quantum-based standards, to improve navigation and timing technologies, and to environmental sensing in novel settings. Single-photon detectors may become possible at far infrared and microwave wavelengths to expand the range of discovery of the dark universe, while non-classical emitters could be integrated for sensing, communication, and computing systems at room temperature.

Today's noisy intermediate scale quantum (NISQ) technology will offer insight into the scientific and technological advances that can address QIS Grand Challenges in areas such as machine learning, simulation of many-body systems for materials discovery, chemical processes, quantum field theory, and dynamics of biological processes. Early exploratory efforts in NISQ systems are already yielding new understanding of these problems. This can help overcome scientific and technological barriers for developing resilient and reliable devices, including networking and storage devices, as well as algorithms and error correction techniques.

5 Creating a quantum-smart workforce for tomorrow

Growing an American quantum-smart workforce with expertise in a broad range of physical, information, and engineering sciences is crucial for assuring sustained progress in QIS. However, America's current educational system typically focuses on discrete disciplinary tracks, rarely emphasizing cross-disciplinary study that equips graduates for complex modern questions and challenges, prominently including QIS. While the responsibility of training students traditionally resides within the academic community, Government agencies and industry can partner with academia to meet the nation's future needs.

Fundamental research is the main mechanism for generating a qualified workforce in QIS. Within the context of the need for individuals with a broad mix of skills, support for the trans-sector and trans-disciplinary approach to research is essential. Students trained in such an environment will be exposed to a diverse yet convergent set of disciplines, along with the associated tools and infrastructure. This will allow students to obtain qualifications and skills required by U.S. industry, national laboratories, and academia. Existing approaches of this nature include special research tracks in academic programs, early career awards from Government agencies, support for focused research groups, and coordinated training with industry. Using and enhancing these programs can increase the size of the QIS workforce. Furthermore, approaches that synthesize these programs, such as industrial collaborations that engaging with a central, fundamental research program, can prepare students with additional skills crucial to entering the workforce in the private sector to further U.S. leadership in quantum science and technology.

Agencies will be encouraged to expand or develop specific programs that foster workforce development and build off each other's strengths and mission. A number of agencies already have existing programs, such as the National Science Foundation's (NSF) Graduate Research Fellowship Program and the Accelerating Discovery Program; the National Defense Science and Engineering Graduate Fellowship Program and the Quantum Science and Engineering Program at the Department of Defense (DOD); Science Undergraduate Laboratory internships, the Graduate Student Research Program, and the Computational Science Graduate Fellowship Program at the Department of Energy (DOE); and the National Institute of Standards and Technology's (NIST) joint research centers that combine Government researchers with university students, postdoctoral scholars, and faculty. These programs can be enriched, modified, and expanded when driven by agency need. Further improvements may include joining existing efforts of different agencies to increase impact, such as by creating joint early-career programs.

Looking to the longer-term horizon, academic faculty provide the bedrock of training programs. Universities should be encouraged to address the workforce development needs by adding tenured or tenure-track faculty within the interdisciplinary themes associated with QIS and consider Quantum Science and Engineering as a discipline for future concentration, exemplified in steps such as creating new departments or thesis tracks. Other avenues include new undergraduate programs, engagement with industry and Government for internships and externships—predominantly for U.S. persons—and new professional development programs, including encouragement for creation of specialized technical programs. These students become ambassadors of their discipline while following a wide range of different paths in their careers, increasing the societal impact of quantum-science education.

Beyond the university, outreach to a broader audience will be essential. A strong comprehensive program in K-12 computational and scientific thinking featuring computer science and physics must start with developing interest at an early stage. A critical role can be played by industry, professional societies, and agencies with vested interest in appropriate outreach, which can help provide access to novel technologies (for example via cloud-based approaches) as well as developing classroom-based learning opportunities and broader connections to the public over various media platforms. At the same time, informal education tools, such as those found in many museums across the Nation, are effective and complementary to the classroom. These overall efforts work best in coordination with the NSTC Committee on STEM and its subcommittees that address STEM and related education.

Improving academic-industrial pathways

One program that is expanding connections across sectors is the recently developed NSF-funded Quantum Information Science and Engineering Network, https://qisenet.uchicago.edu/, also known as "TRIPLETS." This effort promotes small research projects executed by American graduate students over a course of 3 years in close collaboration with an academic principal investigator and an industrial partner, including extended stays at an industrial laboratory or utilizing infrastructure. This enables a direct and smooth transition to an industrial environment upon the TRIPLETS project completion.

Workforce generation efforts and future U.S. workforce needs of the nascent quantum industry should be periodically assessed, through industrial engagement (described in the following section) and work with established STEM efforts. This information can help guide future programs to produce the diverse workforce needed to support the quantum ecosystem. In order to improve the workforce development program over time, an assessment plan of quantum workforce development activities should be encouraged to allow participants to select and expand the most successful strategies and adapt, change, or terminate what does not work. Collaboration with professional societies and organizations, industrial consortia, and local governments are other means of assessing workforce needs.

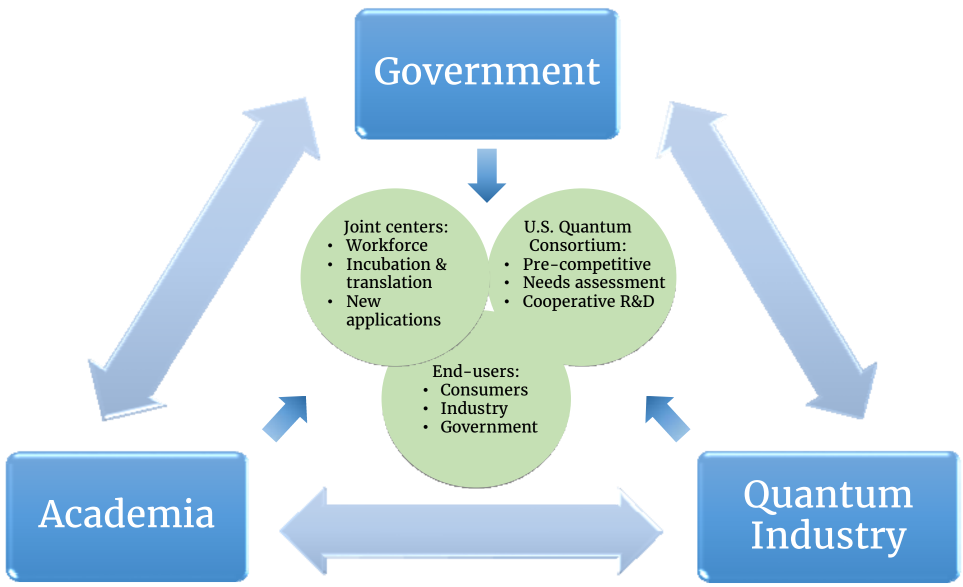
6 Deepening engagement with quantum industry

The revolutionary advances expected to come from QIS have already led to substantial industry attention on QIS research and development. Both large companies and a variety of startups and small businesses are investing heavily in quantum sensing, networking, computing, and supporting technologies. Several have already realized or will soon unveil next-generation quantum sensors, entanglement distribution over small networks, and quantum processors in the 50-qubit range, with plans to continue on a rapid-growth trajectory. In view of the economic and national security importance of QIS the Government will develop means to coordinate with U.S. industry.

A critical element in a robust quantum ecosystem is a strong base of quantum-essential supporting technologies that are not intrinsically quantum in themselves. Current examples include cryogenics, photonics, low-noise microwave amplifiers, and nanofabrication. Thus the consortium should work to identify and stay abreast of these evolving needs, as well as work in partnership with Government agencies and industry to nurture and grow these technologies in cases where they are weak or do not yet exist. Existing approaches such as SBIR and STTR programs that promote innovation for small businesses can be integrated with or combined with other approaches such as joint research centers.

In addition, as a key mechanism for industry engagement, the Government should foster the formation of a U.S. Quantum Consortium with participants from industry, academia, and Government. Like prior consortia such as the Semiconductor Research Corporation, a consortium provides a forum for technical exchanges and discussions to establish a mutual understanding of QIS industry's trajectory, opportunities, and critical technical gaps and projected needs (e.g., for workforce, infrastructure, standards, and road-mapping). Furthermore, the consortium can also provide a venue for joint public-private funding to address infrastructure and technology gaps, and key pre-competitive research and development. Additional input can be provided by advisory bodies as appropriate, such as the President's Council of Advisors on Science and Technology, as well as coordination with other NSTC subcommittees.

Finally, joint research centers— partnerships between industry, academia, and Government—can



accelerate pre-competitive QIS research and development, and in the process help address both the looming need for a greatly expanded and diverse quantum workforce and scientific and applied Grand Challenges. These centers can also facilitate and improve technology transfer from Government research labs. More generally, mechanisms such as incubators for translation from the lab to small companies should be expanded, and roadblocks removed where possible. For a meaningful collaboration environment to exist, intellectual property concerns will also need to be addressed and methods for realizing the development technology emphasized where possible.

7 Providing critical infrastructure

The successful development of technologies based on QIS will enable increasingly more advanced quantum research, but hinges on the availability of suitable tools, facilities, and other infrastructure items. The QIS research and development enterprise is not yet large enough to sustain an industry focused on developing and supplying all the necessary infrastructure. A targeted expansion of the relevant Federal and industrial infrastructure and support activities is needed to accelerate progress and prepare Federal agencies and industry to adopt the ensuing quantum technologies.

The U.S. Government can play a critical role in fostering this field by encouraging programs that target the development and fielding of supporting technologies, ranging from component technologies all the way to sophisticated fabrication and characterization technologies. Agencies will be encouraged to explore mechanisms to provide the QIS research community with increased access to existing and future Federal facilities, including manufacturing facilities that can be repurposed and expanded as well as systems and testbeds for post-quantum applications. As some of these infrastructure capabilities include large user facilities, the Government will consider enhancements to existing Federal facilities and whether Federally-funded QIS research centers should play a role in providing infrastructure or testbeds. Together, these actions will accelerate progress in QIS research and help solidify U.S. leadership in this field.

Enabling the next generation of quantum science

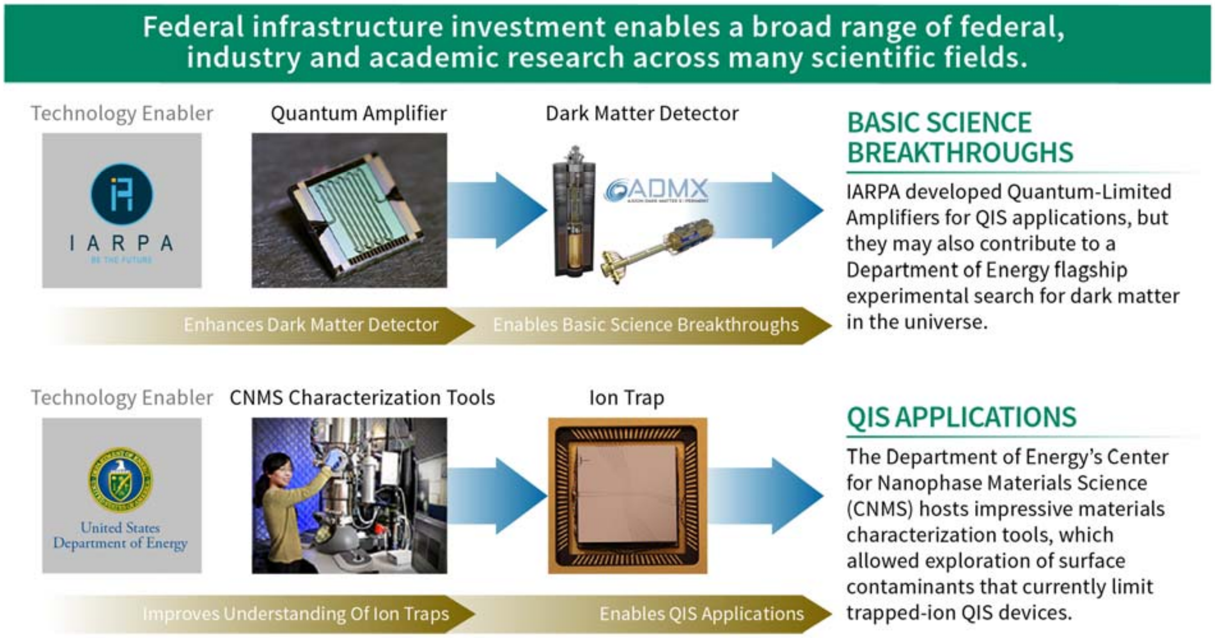
Quantum states are extraordinarily fragile, and successfully using them for applications will require an unprecedented level of control and sophistication. For this reason, QIS will require new classes of high-performance classical components and instrumentation capable of realizing these exacting requirements. These components will cover a broad range of technologies and systems, from ultra-cold cooling systems, to precision electronic and optical systems, and even rather basic components like cables appropriate for carrying quantum signals. The lack of suitable and reliable classical components and equipment is one of the biggest hurdles to surmount in attempting to realize useful QIS devices.

In addition, progress in certain areas of QIS is already limited by the unavailability of specialized materials and advanced technologies for materials characterization. For example, unknown dynamics on the metal surfaces of ion traps limit the performance of ion-based qubits. Recently, U.S. researchers made use of a Rapid Access Proposal to Oak Ridge's Center for Nanophase Materials Science to access a series of sophisticated tools for surface characterization to better understand these defects.

Quantum devices also require sophisticated fabrication capabilities. For instance, over the past decade, access to the Microsystems and Engineering Sciences Application (MESA) fabrication facility has allowed Sandia National Laboratories to develop and mature ion trap devices to a level where they now serve as the base component across numerous academic and industry labs, and enable exploration of quantum computing, quantum sensing, and other related technologies.

Current needs include: classical hardware components, materials characterization and fabrication facilities, critical minerals and materials, and a variety of end-user tools, platforms, and testbeds. The Government will engage with experts and stakeholders, as well as industry and academia, to identify critical infrastructure and map the current infrastructure landscape. For example, the U.S. Quantum Consortium can help determine which of the component technologies will have a sufficient economic base to encourage industrial development, can help develop industry engagement with post-quantum applications, and can also periodically track progress and tap external expertise to evaluate the effectiveness of investments being made. In accordance with evolving needs, these efforts should be on-going.

In addition to bolstering infrastructure, it is important to nurture the adoption of quantum technologies within the Federal Government by cultivating potential end-user agencies. A culture of information sharing has sprung up organically among the personnel at the Federal agencies funding QIS and those looking to leverage future applications. The Government will encourage this culture, and the inter-agency process will provide a sounding board for promulgating such shared interest and promoting the leveraging of Federal investments in advancing each agency's mission. Furthermore, it will explore methods to spur engagement from those end-user agencies that have not yet played a role in developing the technology, but could benefit from the output of this research. Indeed, the impact of QIS will be felt broadly, and it will be important for each agency to be aware of how the quantum revolution may augment its mission space. The establishment of end-user testbed facilities along with training and engagement will allow Federal agencies and stakeholders to explore relevant applications.



Quantum Amplifier: Image courtesy of UC Berkeley / Dark Matter Detector : Image courtesy of Lawrence Livermore National Lab
CNMS : Image courtesy of Oak Ridge National Lab / Ion Trap: Image courtesy of MIT Lincoln Lab

8 Maintaining national security and economic growth

National security needs often drive the advancement of new science and technology and enable economic development through enhanced Government investments, dedicated initiatives, and cross-agency collaborations. At the same time, creating new markets and industries enhance our ability to address national security needs, but the scientific and economic advances can lead to new risks. An appropriate balance between growth and risk can provide long-term benefits.

The technologies that are anticipated to result from intensified research and development in QIS may provide solutions to some of the nation's most pressing national security concerns. For example, advancements in quantum computing may allow for improvements in effective drug discovery, modeling of chemical reactions to enhance corrosion-resistant materials, and optimizing logistics solutions. These and other opportunities in networking and sensing can play a positive role in ensuring national security and defense.

However, there may be challenges to public safety and security that arise from these same technologies. For example, one key quantum algorithm will be able to break public-key cryptography, which secures transactions over the internet. While employing this algorithm is far beyond the current level of technology, the need to protect sensitive data and provide a reliable infrastructure over the long-term requires moving to "post-quantum" or "quantum-resistant" forms of cryptography.

QIS technologies being developed for military and defense applications can also accelerate advancements in the field, leading to substantial economic growth potential through the creation of new industries and products and their transition to consumer markets. The defense and intelligence communities have been strong investors in QIS research and development over the last twenty years, and continue to work across the basic science and applied technology areas to improve the understanding of what is possible with QIS and support the necessary technological base. Enhanced industrial engagement and infrastructure improvements described in the previous sections will also enhance national security and provide economic growth by fostering QIS within the United States rather than leaving innovators to seek support elsewhere.

As the technology evolves, its potential impact on military applications will mean that continual monitoring of export and trade regulations, including the Wassenaar Arrangement control lists and their domestic implementation in the Export Administration Regulations (EAR) and International Traffic in Arms Regulation (ITAR), will be necessary. Furthermore, the defense community has special needs for diverse workforce development; pathways should be added from programs that build a quantum-smart workforce into defense-related research and development. Finally, it is imperative that while developing the QIS enterprise in the United States, the Government also protects intellectual property and economic interests, seeks to understand dual-use capabilities, and supports national-security-relevant applications that emerge from QIS research at every level from basic research to commercialization of QIS technologies. Thus the SCQIS will, in conjunction with other NSTC subcommittees, Federal agencies, and the defense and intelligence communities, ensure consistent application of existing classification and export control mechanisms to provide the largest amount of information possible to American universities and industry about actions related to QIS research.

Improving defense through quantum technologies

Advanced computing capabilities have long been used to enhance both military capability and economic productivity. As such, general purpose quantum algorithms for optimization, machine learning, materials development, and chemical calculations should continue to be explored; although their quantum speed-up is still unknown, any improvements in direct computational ability or in resulting materials and systems could greatly impact military effectiveness.

Beyond computation, new or quantum-enhanced systems could enable the next-generation of sensors and detectors for defense applications. As an example, precision relies on the deep understanding of the quantum properties of atoms; further development can impact both next-generation Global Positioning Systems (GPS) and scenarios where GPS is unavailable. There are further synergies in defense requirements for low size, weight, and power devices via new modalities of sensing.

Exploration of quantum networking also has potential defense value, and could offer added functionality to quantum computation and quantum sensing. Robust solutions to distributing entanglement over multiple length scales—from across a chip to across the world—could enable distributed quantum computers and distributed sensors, with the potential for long-term impact in secure communication. Understanding how quantum effects impact communication, from bandwidth and latency, to security, to novel networking technologies and algorithms, will help realize the best networking systems.

9 Advancing international cooperation

Science, technology, and innovation are cornerstones of U.S. prosperity and economic development and also dominant forces internationally, particularly given the highly interconnected world of the 21st century, where businesses operate globally and scientists and engineers collaborate across borders. Considering the global nature of scientific and industrial enterprises, the United States, including the private sector, has cooperated with foreign partners in QIS research for more than twenty years. These partnerships have accelerated scientific discovery and technological applications while promoting U.S. economic growth and national security.

In order to maintain U.S. leadership and competitiveness in QIS, the United States must work with international partners, even while advancing domestic investments and research strategies. As discoveries accelerate in all sectors, the United States should seek to increase international cooperation with like-minded governments and industrial partners to ensure that technologies resulting from today's investments in basic research and technological development continue to benefit Americans. Sustained domestic investments and strategic international collaboration and cooperation will be vital to this goal.

The Government will focus on three strategic international efforts for QIS. The first effort will be regular reviews of international collaboration activities and partnerships, to identify and track worldwide QIS science and technology trends and identify gaps and opportunities, understand the evolving international QIS landscape, and inform existing programs. Second, the Government will identify and prioritize strategic bilateral partnerships to ensure that the United States continues to attract and retain the best international and has access to international technologies, research facilities, and experts in QIS. Third, the Government should encourage merit-based and transparent fundamental research and innovation systems, and open access to public data arising from QIS research, as appropriate, as well as to advance the development of international standards that enable adoption of new QIS-inspired technologies.

Appendix: Current U.S. leadership in QIS research areas

The United States sustains a vibrant community in QIS. World-leading research groups in the Nation's universities, companies, and national labs have driven progress in many of the critical areas of quantum computing and quantum systems for time-keeping, sensing, networking, and other applications. This status as a leader in quantum research and development is a direct result of the U.S. Government funding agencies and institutions sustained investment in basic and applied research. Both broad and focused programs, built atop a foundation of well-staffed and well-equipped research institutions, have created a talented workforce, encouraged broad innovation and exploration, and dedicated the necessary hard work in physics, materials science, and associated areas necessary to make progress in the development of working, controllable quantum systems. Throughout this effort, the United States has benefited from a many-headed funding model where, for example, one Agency continues to fund critical topics as another changes focus. Furthermore, combining funding driven by mission needs to ensure long-term development with science-driven funding to create the new ideas that seed further innovation provides additional resiliency.

Progress in QIS has recently begun a significant expansion from increases in private sector research and development. Over the last five years, particularly in quantum computing, large IT companies and the venture capital and start-up community have engaged with new QIS opportunities and formed groups and companies to pursue commercialization. It should be noted that all this is possible because of the wealth and know-how that these companies and communities gained from the previous computing and internet revolutions they helped create. The national strategic approach should continue to leverage these strengths of both the U.S. Government funding system and the U.S. innovation ecosystem.

Finally, significant contributions to QIS research have been made in other countries. The field has advanced in the United States in some part by recruiting, collaborating, and competing with science around the world. As a case in point, the first two-qubit gate proposal came from researchers in Europe, but was demonstrated in the Nobel-prize winning group of David Wineland at NIST. This reflects the increasingly global character of the science and technology enterprise. In a field where scientists are still very much fighting nature itself to make progress, humanity's combined effort may be necessary to tackle the challenge. U.S. leadership at this juncture will provide the key ingredients for this success.

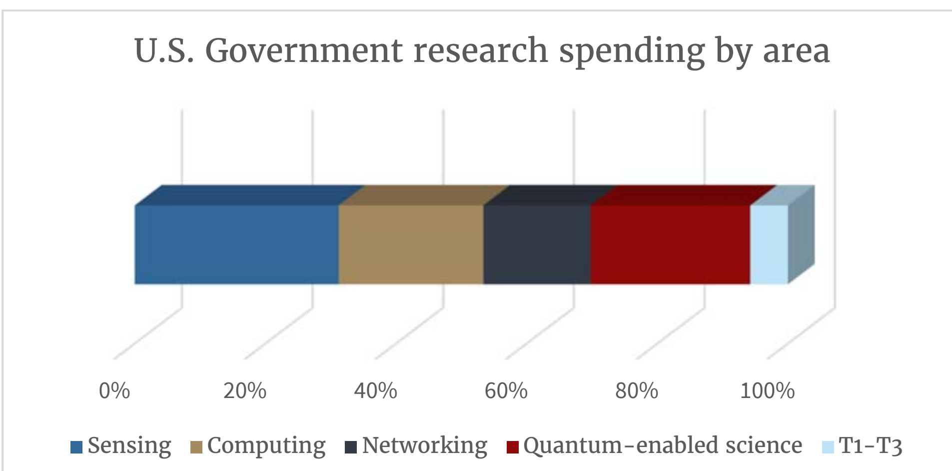
QIS comprises fundamental science and technology across many platforms and topics, and touches upon many agencies. This includes the Department of Agriculture (USDA), Department of Defense (DOD), Department of Energy (DOE), National Institutes of Health (NIH), Department of the Interior (DOI), Department of Homeland Security (DHS), Department of State (State), National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), National Security Agency (NSA), Office of the Director of National Intelligence (ODNI), Office of Management and Budget (OMB), and Office of Science and Technology Policy (OSTP).

The SCQIS assesses the national portfolio using seven broad categories: four in fundamental science (S1-S4) and three in technological development (T1-T3).

S1. Quantum sensing: leveraging quantum mechanics to enhance the fundamental accuracy of measurements and/or enabling new regimes or modalities for sensors and measurement science [**DOD, DOE, DHS, DOI, NIST, NSF, ODNI**]

S2. Quantum computing: from devices and algorithms for analog simulation of quantum systems in the laboratory to controlled digital quantum computers [**DOD, DOE, NASA, NIST, NSF, NSA, ODNI**]
S3. Quantum networking: exploring and using coherent or entangled multi-party quantum states, distributed at distances, for new information technology applications and fundamental science [**DOD, NASA, NIST, NSF**]
S4. Scientific advances enabled by quantum devices and theory advances: improved understanding of materials, chemistry, cosmology, classical computation techniques, and other aspects of fundamental science [**DOE, NIST, NSF**]
T1. Supporting technology: necessary analog, digital, electrical, mechanical, optical, computational, and cryogenic systems and techniques that underpin the fundamental science areas [**DOD**, **NASA, NIST, NSF, NSA, ODNI**]
T2. Future applications: opportunities for improvements in operations research, optimization, machine learning, drug discovery, etc. [**all SCQIS agencies engaged**]
T3. Risk mitigation: necessary infrastructure and support for quantum technologies and their impact, such as quantum-resistant cryptosystems and other post-quantum applications [**DHS, NIST, NSA**]

The Nation's efforts in these areas include a number of agencies that have over the years driven research and development in these seven categories. Current Federal agencies conducting or funding these topic areas are identified above. These seven areas represent the broad foundation necessary to support a full industrial and Governmental effort in quantum information science and technology. The SCQIS also has examined current funding, and finds at the present time that it is primarily focused on S1-S4, as shown in the graph below.



BRINGING QUANTUM SENSORS TO FRUITION

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

MARCH 2022

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of Federal R&D in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the Federal Government. For more information see https://www.whitehouse.gov/ostp.

About the National Science and Technology Council

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

About the NSTC Subcommittee on Quantum Information Science

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

About this Document

This report augments the National Strategy for Quantum Information Science (QIS) by expanding upon policy topics outlined in the *National Strategic Overview for QIS.* Recommendations herein were developed by the SCQIS with input from its Quantum Sensors Interagency Working Group activity.

About the Cover

An artist's rendition of an electron in the Advanced Cold Molecule Electron-EDM (ACME) experiment. Quantum sensors, such as ACME, can serve as powerful probes for physics beyond the standard model of elementary particles, in this case by searching for a permanent electric dipole moment of the electron aligned with its spin axis.

Credit: *Nicolle R. Fuller, NSF* https://www.nsf.gov/news/news_images.jsp?cntn_id=296867&org=NSF

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Table of Contents

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
DOT	Department of Transportation
EAR	Export Administration Regulation
ESIX	Subcommittee on Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
IWG	Interagency Working Group
ITAR	International Traffic in Arms Regulation
LPS	National Security Agency's 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
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NRL	Naval Research Laboratory
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QIST	Quantum Information Science and Technology
R&D	Research and Development
SCQIS	Subcommittee on Quantum Information Science
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USPTO	United States Patent and Trademark Office

Executive Summary

Quantum sensors and measurement devices provide accuracy, stability, and new capabilities that offer advantages for commercial, government, and scientific applications. Examples such as atomic clocks for Global Positioning System (GPS) navigation, and nuclear spin control for magnetic resonance imaging (MRI) are widely used already, with transformative impacts for society. In the near future, Quantum Information Science and Technology (QIST) can enable a new generation of similarly transformative sensors. Furthermore, this process can be accelerated if concerted efforts are prioritized as a part of the National Quantum Initiative (NQI).

Several challenges must be overcome to transition QIST-based sensors from the lab to market and into various mission spaces. Cooperation among industry, academia, and U.S. departments and agencies (hereinafter agencies) can facilitate the requisite science and engineering, especially if a shared vision and mutually beneficial goals are identified. Appropriate partnerships can catalyze progress by linking researchers with potential end users to co-design and field-test prototypes. To this end, recommendations are presented here to coordinate research and development (R&D) and facilitate fruitful applications for quantum sensors. The National Science and Technology Council Subcommittee on Quantum Information Science should leverage its interagency working groups to facilitate the appropriate implementation of the following recommendations:

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.**

These recommendations augment the U.S. strategy for QIST by building upon the *National Strategic Overview for Quantum Information Science* and the NQI Act. The long-term goal is to promote economic opportunities, security applications, and the progress of science through the development of quantum technologies. In the near- to mid-term, i.e., the next 1-8 years, acting on these recommendations will accelerate key developments needed to bring quantum sensors to fruition.

Collaborations between QIST R&D leaders (technology producers) and potential users will stimulate discussions and the field testing of devices. End users in agencies such as NIH, DHS, USDA, NOAA, NASA, DOD, and USGS can engage in appropriate efforts to apply QIST devices that were created with initial support from NIST, NSF, DOE, DOD, or NASA. Then, as value propositions and priorities evolve, coordination can spur R&D on key components, such as laser systems, integrated optics, and other cross-cutting and enabling technologies. Advances in quantum sensing components may also aid in the development of quantum computing and networking capabilities, for example, with chip-scale atomic processors. At the same time, translation of QIST research into marketable products and services can benefit from innovation-friendly practices and a robust technology transfer ecosystem.

I. Introduction

Due to their improved accuracy, stability, sensitivity, and precision, quantum sensors offer some advantages over traditional technologies. In addition, quantum measurement devices and modalities without classical counterparts enable some tasks that were previously unfeasible. For example, single atomic spins can map magnetic fields with nanometer resolution. Matter-wave interferometers can monitor gravitational fields with unprecedented accuracy. Entanglement and many-body quantum states may enable even more profound capabilities, such as non-invasive imaging or measurement precision beyond the standard quantum limit. However, realizing such new technology and deriving major benefits for society can take years or even decades of innovation. A goal of the National Quantum Initiative (NQI) is to accelerate this process and bring more quantum sensors to fruition.

Successful exemplars of quantum sensors include atomic clocks, which have many applications including GPS navigation, and also magnetic resonance imaging (MRI) scanners, which are widely used in medicine. Beyond these well-known cases, quantum sensors at various stages of development are on the horizon, and some will offer disruptive capabilities for industry, defense, and science. However, it is difficult to predict which platforms will become most useful, as translating research from the lab to market can take long and circuitous pathways.[1] To wit, the inventors of early atomic clocks probably never envisioned the advent of the ride hailing and food delivery apps that currently use atomic clocks to facilitate pick-up and drop-off via GPS navigation. In a similar spirit, tomorrow's enterprises may leverage novel quantum sensors for applications that are not yet foreseen.

Crossing the "valley of death," i.e., maturing proof-of-principle prototypes into economically viable devices, requires overcoming many hurdles.[2] Careful handoffs are needed between funding agencies, scientists, engineers, innovators, investors, manufacturers, and end users. Still, as with many emerging technologies, revolutionary innovations may fail to find a market for many reasons. Obstacles include competition with more familiar classical technologies, and the often incremental or iterative process of improving the size, weight, power and cost (SWaP-C), and functionality of devices. Cycles of development often require substantial and long-term efforts to reengineer key components. Even after business concepts are identified, supply chains require time to establish. Economies of scale can be elusive and may depend on other sectors. Navigating these challenges requires synergistic actions among academic, industrial, and government actors, which can be orchestrated with sound policy.

The policy recommendations presented here are designed to address gaps where coordination is needed and can substantially accelerate the discovery, development, and utilization of quantum sensors. For example, fostering joint ventures between QIST experts and potential consumers can stimulate use-inspired basic research and field testing. Joint efforts can pioneer applications and translate inventions towards commercial, mission-relevant technologies. The early adoption of new devices, even if it entails some risk or deviates from the status quo, can lead to discoveries and provide benefits such as expertise, intellectual property, and first-mover advantages. These actions can also grow the market for quantum sensors and supporting technologies, and galvanize the community.

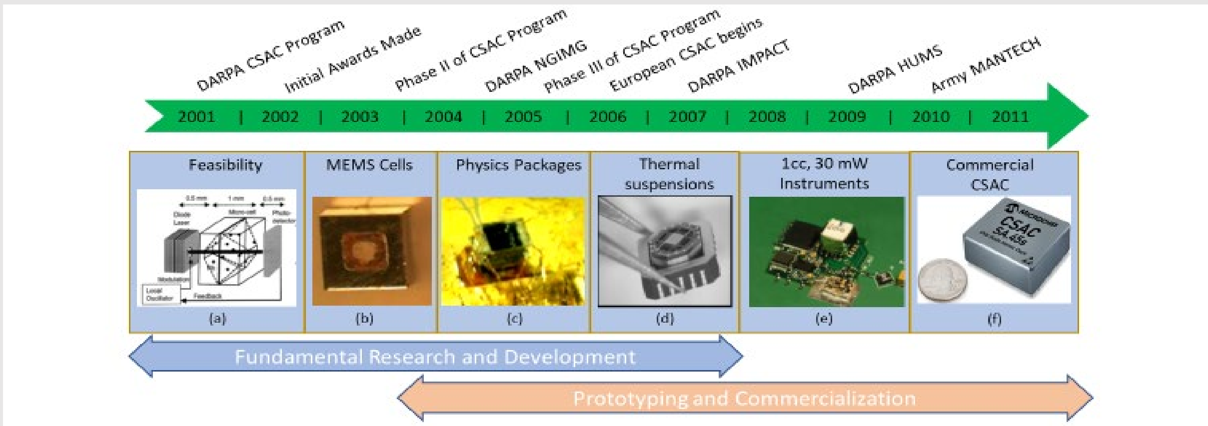
To mature a quantum sensing technology, a compelling vision with tangible goals can motivate the necessary theoretical, experimental, and engineering developments. For example, Box 1 highlights how the Chip Scale Atomic Clock (CSAC) incorporated key technologies – compact lasers, microfabrication, and the atomic physics of coherent population trapping – to deliver commercial devices for precision

[1] 'Return on Investment Initiative for Unleashing American Innovation,' doi:10.6028/NIST.SP.1234

[2] https://www.nist.gov/blogs/taking-measure/mind-gap-bridging-valley-death-us-biomanufacturing

time-keeping on a chip with a hundred-fold improvement over existing products of comparable scale. The CSAC development was motivated by clear use cases and leveraged synergistic efforts among industry researchers, agency program officers, and national laboratory teams. The goal was focused by a realistic vision for an attainable quantum sensor and fueled by a steadfast series of investments (roughly $100 million over ten years) from agencies and industry.

Box 1: Timeline of Development for 1st Generation Chip Scale Atomic Clocks



The Chip Scale Atomic Clock (CSAC) program, initiated by DARPA and catalyzed by a 2001 NIST workshop, built upon several advancements made in compact lasers, coherent population trapping, and microfabrication. From fundamental R&D (a-c),[3] to engineering and prototyping (d-e),[4,5] to an example of a commercialized product (f),[6] the CSAC effort took over a decade of sustained investments totaling almost $100 million, with coordination amongst academia, government, and industry. Multiple programs and industry partnerships contributed to CSAC development, resulting in key component technologies and commercialization, with over 100,000 sold.[7] CSACs are finding applications in the DOD, geophysical sensing, and cellular communication.

The NQI Act[8] provides for a coordinated federal program to accelerate quantum information science (QIS)[9] R&D for the economic and national security of the United States. It calls for cooperation across the civilian, defense, and intelligence sectors on QIST R&D. The NQI Act authorizes NIST, NSF, and DOE to strengthen QIS programs, centers, and consortia, and the National Defense Authorization Act (NDAA) authorizes related efforts in the defense sector. To guide these actions, the NQI Act legislates responsibilities for the National Science and Technology Council (NSTC) Subcommittee on QIS (SCQIS), and the FY 2022 NDAA legislates responsibilities for the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX).[10]

These subcommittees are augmenting the *National Strategic Overview for QIS*[11] with strategy documents containing recommendations, such as this one on quantum sensors, which can be found on www.quantum.gov.[12] The rest of this report is organized as follows: Section II provides background on quantum sensors, Section III presents recommendations, and Section IV proposes timelines for action.

[3] Images reproduced from 'Chip-scale atomic devices,' doi:10.1063/1.5026238
[4] Image reproduced with permission from 'The chip-scale atomic clock – low power physics package'
[5] Image reproduced with permission from 'The chip-scale atomic clock – prototype evaluation'
[6] Image reproduced with permission from Microchip Technology Incorporated
[7] https://www.nist.gov/noac/success-story-chip-scale-atomic-clock
[8] 15 USC §§ 8811-8815, 8831, 8841-8842, 8851; https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[9] 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.
[10] NDAA for FY 2022, Public Law 117-81; https://www.congress.gov/117/plaws/publ81/PLAW-117publ81.pdf
[11] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[12] See www.quantum.gov

II. Quantum Sensor Exemplars

Quantum sensors are devices that use quantum mechanical properties, such as atomic energy levels, photonic states, or the spins of elementary particles, for metrology. They offer precision measurement techniques for science, technology, and industry. Several reports already discuss the impact of quantum sensors in various domains: positioning, navigation, and time keeping; local and remote sensing; biomedical, chemical, and materials science; and fundamental physics and cosmology.[13-21]

Box 2 lists a few quantum sensor technologies and anticipated applications. These exemplars are not intended to be comprehensive. They merely illustrate how quantum technologies are poised to provide benefits for health, security, commercial, industrial, and scientific uses. The discussion in this Section thus provides background and context for the recommendations presented in Section III.

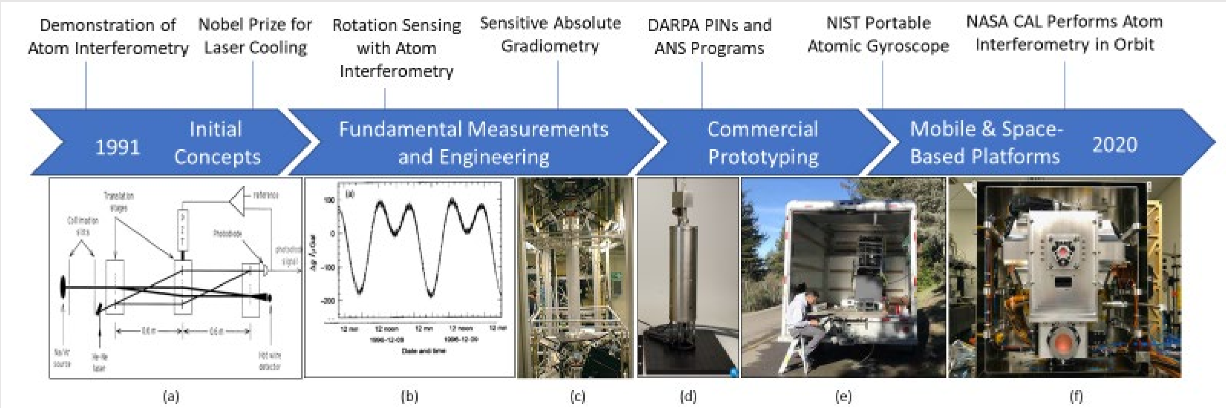
Box 2: Quantum Sensor Exemplars
1. **Atomic clocks** for positioning, navigation, networking, and metrology.
2. **Atom interferometers**, e.g., gravimeters for remote sensing and accelerometers for navigation.
3. **Optical magnetometers** for bioscience, geoscience, and navigation.
4. **Devices utilizing quantum optical effects** for local and remote sensing, networks, and fundamental science.
5. **Atomic electric field sensors**, e.g., Rydberg atoms for GHz-THz radiation detection.

Atomic clocks are key for GPS navigation. Access to auxiliary networks of atomic clocks and high-precision time-transfer protocols can provide resilience for navigation systems when standard GPS signals are unavailable. Atomic clocks currently enable internet and cell phone communication and are necessary for secure or high-bandwidth applications. Geology, seismology, oil exploration, power grid operations, and the financial services sector already benefit from CSACs discussed in Box 1. Radio telescopes use atomic clocks to support very-long-baseline interferometry. Dramatic improvements in state-of-the-art atomic clocks using cold atoms, optical transitions, and frequency combs are creating new opportunities. One example is geodesy using gravitational redshifts. Trace gas detection (e.g., for monitoring methane leaks) and enhanced spectrometer calibration (e.g., with "astro-combs") are additional applications of atomic-clock-enabling technologies like frequency combs. Advanced clocks also enable fundamental physics searches for dark matter and searches for variations of fundamental constants. Improved timekeeping in space will be needed for deep space navigation, while on Earth, space-based clocks can support time-transfer protocols and improved GPS accuracy, e.g., for monitoring changes in sea level. Like many quantum sensors, CSACs leverage technology such as compact lasers that were originally developed for other industries, with economies of scale.

[13] 'Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science & Computing,' doi:10.2172/1358078
[14] 'Quantum Science Concepts in Enhancing Sensing and Imaging Technologies: Applications for Biology: Proceedings of a Workshop,' doi:10.17226/26139
[15] 'Manipulating Quantum Systems,' doi:10.17226/25613
[16] 'Opportunities for Basic Research for Next-Generation Quantum Systems,' doi:10.2172/1616258
[17] 'Future directions of quantum information processing,' https://basicresearch.defense.gov/Portals/61/Documents/future-directions/Future_Directions_Quantum.pdf?ver=2017-09-20-003031-450
[18] 'Nuclear physics and Quantum Information Science,' https://science.osti.gov/-/media/np/pdf/Reports/NSAC_QIS_Report.pdf?la=en&hash=91703C70429F2B7D634CBC10573079858926141D
[19] 'Opportunities for Nuclear Physics & Quantum Information Science,' arXiv:1903.05453
[20] 'Assessment of the Future Economic Impact of Quantum Information Science,' https://www.ida.org/-/media/feature/publications/a/as/assessment-of-the-future-economic-impact-of-quantum-information-science/p-8567.ashx
[21] See additional reports on QIST posted on www.quantum.gov

Atom interferometers used as gravimeters and gravity gradiometers hold promise for geoscience studies of volcanology, groundwater, mineral deposits, tidal dynamics, and the cryosphere (i.e., the distribution of ice on the planet). Box 3 highlights some milestones for atom interferometers on the timeline from invention to commercial applications. These instruments may soon be able to map underground structures and voids, with potential uses for vehicle inspections and tunnel detection. Improved gravimeters offer the potential to reduce costs in civil engineering and geological surveys. Fundamental physics applications include measurements of the universal gravitational constant (big *G*), tests of the equivalence principle (the universality of free fall), measurements of gravity on the millimeter scale, searches for dark matter particles, and possible alternative approaches to gravitational-wave detection.[22] Atom interferometers also make competitive gyroscopes and accelerometers for inertial navigation, minimizing the need for sonar or GPS in certain situations, and potentially reducing long-term errors compared to traditional inertial measurement technologies. Applications to gyro-compassing, satellite pointing, guidance, gravity mapping for navigation, and undersea obstacle avoidance may be forthcoming.

Box 3: Atom Interferometry Timeline from Laboratory Studies to Commercial Applications

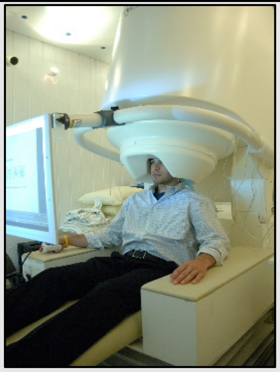


The field of matter-wave optics was launched by de Broglie's hypothesis that particles propagate like waves. Atom interferometry then benefited from key work on laser trapping and cooling of atoms, coherent momentum transfer from light to atoms, photonics, and nanotechnology. Modern demonstrations of atom interferometry were pioneered in 1991 (a),[23] and the field grew with support from multiple agencies including NSF, NIST, ARO, ONR, DARPA, NASA, and DOE. Atom interferometry has applications in gravimetry (b),[24] inertial navigation, civil engineering, geoscience, and the measurements of fundamental constants. Sustained investments over 30 years have taken atom interferometers from laboratory instruments (c)[25] to space based platforms, leading to new companies and commercial prototypes (d),[26] mobile units (e),[27] and atom interferometry experiments performed in orbit (f)[28] with NASA's Cold Atom Lab in 2020. Even with these advances, engineering challenges still need to be overcome to facilitate commercial uses of atom interferometry. For example, focused work is needed on laser systems, integrated optics, atomic sources, vacuum systems, and quantum control.

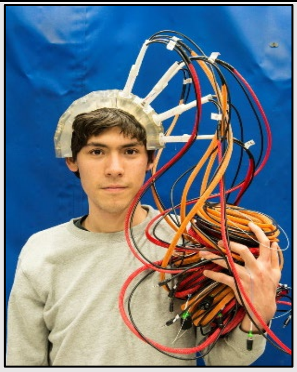
[22] https://news.fnal.gov/2019/09/magis-100-atoms-in-free-fall-to-probe-dark-matter-gravity-and-quantum-science/
[23] Image reproduced with permission from 'An interferometer for atoms,' doi:10.1103/PhysRevLett.66.2693
[24] Image reproduced with permission from 'High-precision gravity measurements using atom interferometry,' doi:10.1088/0026-1395/38/1/4
[25] Image reproduced with permission from 'Light-pulse atom interferometry,' arXiv:0806.3261
[26] Image reproduced with permission from https://aosense.com/product/gravimeter/
[27] Image reproduced with permission from 'Gravity surveys using a mobile atom interferometer,' doi:10.1126/sciadv.aax0800
[28] Image reproduced from https://science.nasa.gov/technology/technology-highlights/quantum-technologies-take-flight

Optical magnetometers based on atomic spins in vapors, Bose condensates, or solid-state systems such as nitrogen vacancy (NV) centers in diamond, can provide functionality for local and remote sensing, mapping, and navigation. Magnetometers enable biomedical studies of neurological function, for example, with magneto-encephalography (MEG) for understanding Alzheimer's disease, Parkinson's disease, and cognition. Technologies such as MEG (Box 4) are complementary to functional MRI, electroencephalography (EEG), and cryo-electron microscopy in biomedical sciences. NV centers also enable NMR spectroscopy (Box 5) of chemical shifts in micrometer scale samples, suitable to study protein dynamics in individual cells.[29] Quantum diamond microscopes based on NV centers can map magnetic fields with unprecedented spatial resolution for studies of geoscience, electronics, and biology. Optical magnetometers are also valuable for vector magnetometry and measurements of absolute magnetic field magnitudes. Optical magnetometers can also support non-invasive testing of biological samples and new tools for surface science.

Box 4: Vapor Cell Magnetoencephalography (MEG) Highlight



(a)



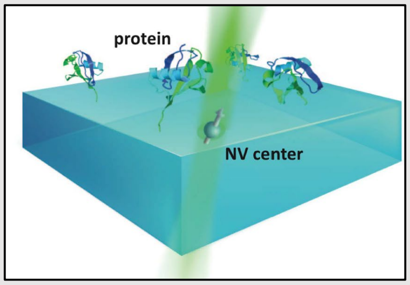
(b)

Superconducting quantum interference device (SQUID) based MEG devices (a)[30] require cryogenic cooling, with large footprints and overhead. They are therefore confined to a few geographical locations, and while applicable to the field of medical research, they are unlikely to realize large-scale clinical use. Vapor cell-based MEG devices (b)[31] can approach and even exceed the sensitivity limits of SQUID MEGs, without the need for cryogenic cooling or the large footprint for operations. One application of these smaller, more transportable MEG devices, is the potential for diagnosing traumatic brain injuries in the field.

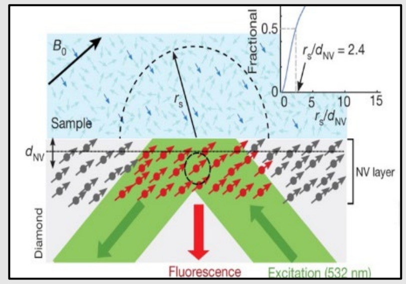
Fundamental physics applications of advanced quantum sensor technology include searches for a permanent electric dipole moment (EDM) of particles such as the neutron or electron. This leverages the *precision frontier*, as opposed to the energy frontier, to test theories that go beyond the Standard Model of elementary particle physics. One such project, the Advanced Cold Molecule Electron (ACME) EDM experiment is highlighted in the cover art for this report.[32] Approaches such as this are sometimes called "tabletop experiments with skyscraper reach,"[33] which present new opportunities at the intersection of high energy physics with atomic, molecular, and optical physics.[34]

[29] 'High-resolution magnetic resonance spectroscopy using a solid-state spin sensor,' doi:10.1038/nature25781
[30] Image reproduced from https://images.nimh.nih.gov/public_il/image_details.cfm?id=80
[31] Image reproduced from https://www.nist.gov/news-events/news/2016/07/detecting-brain-waves-atomic-vapor
[32] 'Advanced Cold Molecule Electron EDM Search,' https://www.nsf.gov/awardsearch/showAward?AWD_ID=1404146
[33] https://nsf.gov/awardsearch/showAward?AWD_ID=1707700; http://schmidta.scripts.mit.edu/tabletop_workshop/index.html
[34] NSF Dear Colleague Letter: Searching for New Physics Beyond the Standard Model of Particle Physics Using Precision Atomic, Molecular, and Optical Techniques, https://www.nsf.gov/pubs/2020/nsf20127/nsf20127.jsp

Box 5: Nitrogen Vacancy Center Magnetometry Highlight



(a)



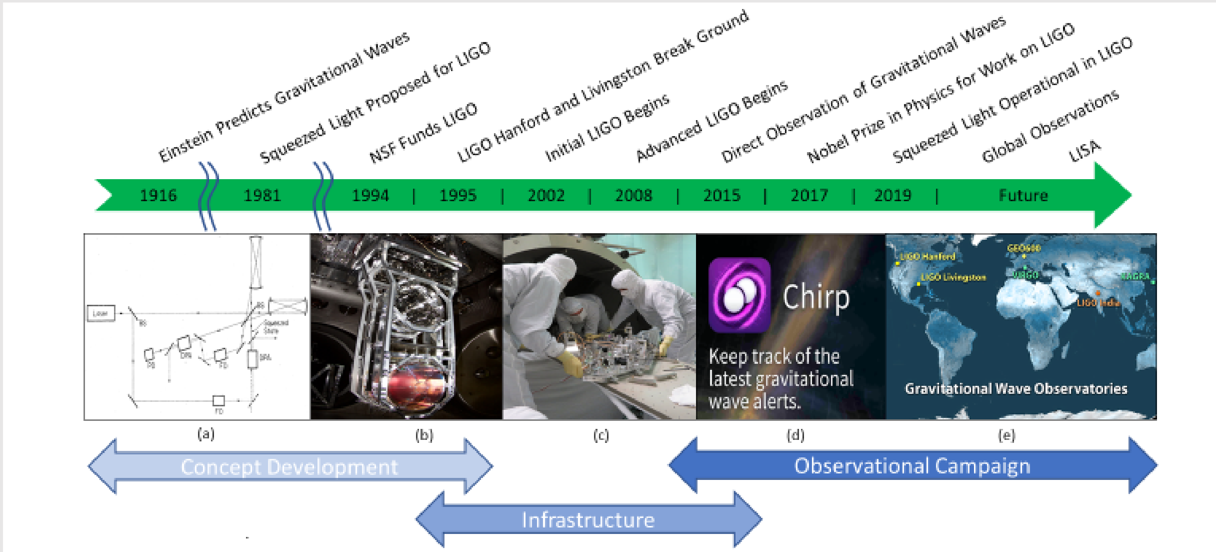
(b)

Nitrogen Vacancy (NV) centers in diamond allow for magnetometry and nuclear magnetic resonance (NMR) spectroscopy and imaging with spatial resolution approaching the nanometer scale. R&D on NV centers has spanned over two decades, with participation from NSF, NIST, DOE, DOD, and NIH. Notable achievements include the detection of multiple nuclear species within ubiquitin proteins, such as in (a),[35] NMR spectral resolution using NV centers, such as in (b),[36] the demonstration of scanning confocal microscopy with single NV centers, nanoscale magnetic field sensing, single cell imaging using quantum diamond microscope, and detection of single neuron excitations in live specimens. A possible near-term application for an NV diamond magnetic imager may be to detect changes in the conduction velocity of action potentials caused by diseases such as multiple sclerosis.

Devices utilizing quantum optical effects provide opportunities to understand, and in some cases beat, the standard quantum limit in microscopy, spectroscopy, and interferometry. Non-classical states of (N) photons enable measurements reaching towards the Heisenberg limit (characterized by uncertainty in phase that scales as $1/N$ as opposed to $1/\sqrt{N}$). As an exemplar, "squeezed light" allows NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO) and its international counterparts, Virgo and KAGRA, to operate below the traditionally expected noise floor. Using squeezed light has significantly increased the detection rate for black hole collisions, effectively expanding the volume of the universe that can be studied with LIGO.[37] Quantum optical effects thus provide a valuable resource for multi-messenger astrophysics, recognizing that gravitational-wave signals can be precursors to gamma, visible, radio wave, and possibly neutrino events. The successful use of squeezed light to enhance cutting-edge instrumentation is a tribute to what can be achieved with sustained support of fundamental theory, experimental research, and targeted engineering. Advances in each were needed to achieve the results. A healthy tolerance for risk, substantial coordination, and a major focus on operational campaigns are hallmarks of what enabled quantum optics to be harnessed for enhanced LIGO functionality. Box 6 portrays the progress from initial conceptualization to the current state of LIGO.

[35] Image reproduced with permission from 'Nuclear magnetic resonance detection and spectroscopy of single proteins using quantum logic,' doi:10.1126/science.aad8022
[36] Image reproduced with permission from 'High-resolution magnetic resonance spectroscopy using a solid-state spin sensor,' doi:10.1038/nature25781
[37] https://www.ligo.org/

Box 6: A Timeline of LIGO Development from Theoretical Concepts to International Observation Campaigns



NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO) is the result of over four decades of basic research and over $1 billion in investments. The existence of gravitational waves was predicted by Einstein a century before the first observation, and the use of squeezed light to beat the standard quantum limit was first proposed in 1981.[38] At the time of initial funding, LIGO accounted for the largest single award made by NSF. It took over 20 years from the initial investment to produce an observation of gravitational waves; a testament to the value of sustained and patient management. The 2017 Nobel Prize in Physics was awarded to three American physicists for the importance of the work done at LIGO and the observation of gravitational waves. To date, there have been over 90 detections of gravitational wave events resulting from black hole mergers, black hole-neutron star mergers, and a neutron star collision. There are international efforts underway to build additional terrestrially-based interferometers, and also a space-based interferometer called LISA. The thumbnails from left to right are pictures of an early schematic for using squeezed light in the detection of gravitational waves (a),[38] the quadruple pendulum suspension system in advanced LIGO (b),[39] the installation of optical circuitry for squeezed light in LIGO (c),[40] apps which can alert a mobile phone of gravitational wave detection events (d),[41] and a map of the current and in-development gravitational observatories across the world (e).[42]

The field of quantum optics also provides a basis for super-resolution and non-invasive, or less-invasive, imaging. These concepts may provide new types of microscopes for biomedical science. Single-photon and photon-number-state detectors can be applied to DNA sequencing, tracking of enzyme activity, particle physics, dark matter searches, quantum networking protocols, and remote sensing with low light levels, e.g., advanced LIDAR. Quantum sensors via quantum state tomography, quantum gate set tomography, and quantum process tomography may elucidate the behavior of quantum computer prototypes and components. These sophisticated probes for materials and devices may lead to a better understanding of superconducting qubits, trapped ion qubits, NV centers in diamond, and other designer impurities in solid state materials.

[38] Image reproduced with permission from 'Quantum-mechanical noise in an interferometer,' doi:10.1103/PhysRevD.23.1693
[39] Image reproduced from https://www.ligo.caltech.edu/image/ligo20091202a
[40] Image reproduced from https://news.mit.edu/2019/ligo-reach-quantum-noise-wave-1205, photo credit: Lisa Barsotti
[41] For example, app image reproduced with permission from Samuel Morell, University of Exeter
[42] Image reproduced from https://www.ligo.caltech.edu/image/ligo20160211c

Atomic electric field sensors can use Rydberg atomic states as a transducer or a quantum antenna to measure electromagnetic fields in a wide range of frequencies spanning DC (0 Hz) to THz (10^{12} Hz).[43] Detection, signal processing, and imaging of THz radiation can be accomplished with optical readout using coherent spectroscopy methods. This technology provides opportunities for remote sensing and new capabilities in electrometry, potentially expanding access to and enabling new applications in the THz regime. Additionally, atomic electric field sensors provide an opportunity to reduce the size of antennas and improve radio frequency filtering. Other applications include extending the range between cellular towers and the acquisition of signals with a wide dynamic range.

Discussion: Quantum sensing provides tools for precise metrology based on revolutionary approaches, as illustrated in this section. The broadly defined fields of quantum sensing, networking, and computing each contain important scientific frontiers - quantum frontiers[44] - on their own. Furthermore, R&D work in these domains can be mutually reinforcing and cross-connect with other fields. For example, support technology for quantum sensors, such as laser systems, integrated optics, cryogenics, and specialized materials, can have cross-functional uses in quantum computing and quantum networking. Quantum networks leveraging dark fiber and free-space optics may enable radically new quantum sensors such as long-baseline telescopes that could use entanglement as a resource. As another illustration, techniques first demonstrated in quantum computing experiments are enhancing the performance of atomic clocks using ion traps and quantum logic spectroscopy.[45] Thus, research on quantum sensors can benefit from, and also pave the way towards, more sophisticated systems for quantum information processing.

Workforce needs must be considered as part of the national strategy for quantum sensors, recognizing that progress relies on an adaptable, diverse, and talented workforce to explore quantum frontiers. Expanding the QIST workforce will take time, resources, and deliberate actions discussed in the recently released national strategic plan for QIST workforce development.[46] Fortunately, R&D on quantum sensors provides dynamic and rewarding training opportunities for the next generation of scientists and engineers, where people can gain a wide variety of skills.

Near-term opportunities for quantum sensors to benefit society are numerous. However, the vast space of possible applications and the broad range of quantum technologies illustrated in this Section causes challenges which will be discussed in the next Section. For example, quantum sensor R&D efforts are somewhat diffuse and unfocussed; many quantum sensor concepts are at low levels of technology readiness; and many sensor concepts still require substantial engineering with commensurately substantial funding for the development of key components. It is unlikely that all of these barriers can be overcome by any one agency acting in isolation, because the science and engineering problems are diverse and new.

A coherent strategy that motivates cooperative efforts on carefully chosen outcomes for research and development on quantum sensors is needed. Policy recommendations for that purpose are discussed next, in Section III.

[43] 'Waveguide-coupled Rydberg spectrum analyzer from 0 to 20 GHz,' doi: PhysRevApplied.15.014053
[44] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[45] 'Spectroscopy using quantum logic,' doi:10.1126/science.1114375
[46] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf

III. Recommendations for Bringing Quantum Sensors to Fruition

Sensing is arguably the most mature subcategory of quantum technology. In comparison, quantum computing and quantum networking are at earlier, albeit dynamic, stages of development. Given the state of play, several quantum sensors appear poised to produce impacts for society in the near-term, provided that some key challenges can be overcome. Furthermore, R&D associated with the NQI can be instrumental for the realizing the full benefit of quantum sensors. The United States can spur development of quantum sensors with actions recommended in this Section.

Challenges to Address: Bringing new quantum sensors from proof-of-concept designs to fieldable products still requires overcoming many hurdles. Key challenges are briefly summarized here. For one, the vast application space and wide variety of potential user requirements makes it difficult to focus work on specific applications or requirements. Furthermore, the market drivers and commercial value of many quantum sensors are still being determined. Hence, R&D efforts are diffuse. Meanwhile, the long road from basic research to successful products requires substantial and sustained funding, often with several coordinated thrusts. Given the varied needs of different user communities, a long-term strategy should be developed to align multiple agencies and unite private sector stakeholders around the development of some particular applications and key supporting technologies. A cohesive, system-wide approach is especially important for R&D efforts that may be too costly for any single agency, university, or company to sustain on their own. Additional coordination with the private sector to efficiently mature quantum technologies across the valley of death may benefit from coordinated efforts to identify and disseminate effective practices for managing intellectual property, acquisitions, research security, and appropriate partnerships. Innovation-friendly practices can facilitate spin-off technologies and companies, and a robust ecosystem for technology transfer.

Four policy recommendations to address these challenges are presented in Box 7. To facilitate implementing these recommendations, the NSTC Subcommittee on QIS and its interagency working groups should help coordinate supporting actions discussed throughout this Section.

Box 7: Recommendations to Facilitate the Development and Utilization of Quantum Sensors

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.**

Recommendation 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.

Challenges Addressed: Many scientists conducting basic research lack expertise in vast domains where their work might eventually be applied. This includes familiarity with current (competing) technologies and the rigors of deploying sensors in operational environments. Finding experts and end users with that complementary knowledge can be challenging, and the payoff may require long durations with many cycles of development. These timeframes may not align neatly with criteria for promotion and tenure. The (perceived) lack of programmatic resources or agency support for new joint projects can slow progress. It is also difficult to forecast if or when experiments and demonstrations will lead to commercially or scientifically relevant devices or help agencies accomplish their missions.

Discussion of Recommendation: Agencies leading QIST R&D, such as NIST, NSF, DOE, DOD, NASA, and those within the intelligence community, should engage with potential end users for quantum sensor prototypes to jointly test, develop, and disseminate findings for end-user applications. The goal for this recommendation is to accelerate fundamental R&D, testing, and utilization of prototypes. These agencies should seek appropriate partnerships with end users in U.S. Government, industry, and academia who can apply quantum technologies to improve the way technology consumers accomplish their respective goals or missions. Field testing and early adoption of select relevant exemplars should stimulate developers to work on the most important specifications and functionality. At the same time, joint efforts should benefit the end users by providing new capabilities, first-mover advantages, and an increasing awareness of emerging technologies. Collaborations of this nature should also create opportunities to invest in use-inspired basic research and pioneer entirely new applications.

A first step for engaging end users is to share information, for example, at workshops, professional conferences, and through follow-up discussions and publications. Educating agency leadership, field scientists, and program officers about the capabilities of quantum sensors can be done with briefings, seminars, and working groups. Quantum 101 briefings can provide an overture or foothold for further discussions. While some agencies have engaged in the development of quantum sensors for decades, this knowledge can still be siloed within a few laboratories or divisions. Hence, sharing information about emerging quantum sensors with end users and agency leadership across the U.S. Government is an important step. This professional outreach can include staff at national laboratories, DOD laboratories, and a broad list of agencies that could utilize quantum sensors, including, e.g., NASA, NIH, DHS, NOAA, USGS, USDA, and DOT. Recognizing the ongoing and complementary work being done around the globe on quantum sensors and component technologies, international cooperation should be leveraged as appropriate. Memoranda of understanding (MOUs) and agreement (MOAs), or annexes to existing MOUs and MOAs, should be encouraged as a means to formalize collaborations and identify roles and responsibilities.

Overcoming barriers to these types of collaborations may require cultural shifts within agencies and academia. For example, promotion and tenure committees could acknowledge a wider variety of contributions to QIST development and not restrict professional reward solely to projects with neatly packaged milestones or publications. Instead, nurturing a culture of discovery that celebrates multidisciplinary efforts can help ensure that attention is not diverted from potentially transformative approaches. Agency program officers also need resources to explore new opportunities, work across boundaries, and support joint ventures. Cultural shifts of this nature require sustained efforts and leadership from multiple agencies and institutions to allocate resources and take appropriate risks.

Recommendation 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.

Challenges Addressed: Quantum technologies can sound exotic and be surrounded by exaggerated claims. Unrealistic expectations or misunderstandings about potential applications are unfortunately common consequences. There are also potential end users who are unaware of the existence of certain quantum sensors, leading to missed opportunities. Prior to developing economies of scale, it is difficult to project when or if lab demonstrations will become commercially viable or help agencies accomplish their missions. Comparisons with existing, classical alternatives and benchmarks are not straightforward, for example, because classical sensors may have decades of R&D. These challenges complicate seeing ahead to competitive devices that can be supported by procurement. Satisfying SWaP-C constraints for quantum sensors may depend on supporting technology that is still undergoing fundamental R&D, which may give the false impression that a given quantum sensor concept will never be viable. Furthermore, the practical value of a sensor depends on many factors, including performance in real-world environments. Specifications such as response to environmental noise, reliability, bandwidth, duty-cycle, and operational dead time are important, but often are not the first priority for scientists or inventors to optimize in early prototypes. Yet these factors are highly relevant for field deployment. Hence, potential end users should help to judge this trade-space.

Discussion of Recommendation: Agencies using sensors should identify a few relevant quantum technologies and investigate them with dedicated efforts, invoking partnerships, MOUs, and MOAs as appropriate. Potential end-user agencies (consumers) within the U.S. Government could include DHS, NIH, USDA, USGS, NOAA, as well as components of DOE, DOD, and NASA that might be initially outside of the QIST research ecosystem. National laboratories, federally funded R&D centers, and scientists in academia could be early adopters as well. Joint efforts among QIST R&D practitioners and these end users can be prioritized to field-test, co-design, and develop new quantum sensor prototypes and applications. Agencies can use the SCQIS and its working groups to help identify potential partnerships.

Time and resources should be allocated to encourage agency staff to collaborate with QIST R&D leaders in other government agencies, the private sector, and academic research institutions, both domestically and internationally. Attention should be given to potentially disruptive technologies. Establishing collaborations early in the R&D process will help to explore the value added from quantum modalities, recognizing that revolutionary approaches often take time to produce results. These efforts should assess the impact of quantum sensing to end-user agency missions, and prioritize use cases where quantum sensors address unsolved capability gaps or result in large-scale improvements.

Feasibility studies should result in reports with actionable plans and recommendations for developing quantum sensing technologies, along with descriptions of use cases with requirements or metrics that would need to be met for new sensors to impact an agency or research area. Producing and sharing these reports will inform realistic expectations and give QIST R&D leaders more clearly delineated goals, ultimately fostering future collaborative research undertakings.

These joint efforts should augment, not supplant, ongoing quantum sensor research. Importantly, coordination like this can provide a pull (complementary to a technology push) for early demonstrations of capabilities in realistic, mission-relevant environments. They can also leverage dual-uses of quantum technologies to develop robust markets. Users can bring fresh perspectives that may lead to entirely new applications or new approaches for using existing sensors.

Recommendation 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.

Challenges Addressed: Access to key supporting technologies is a challenge due to the demanding technical requirements and substantial cost of the engineering needed to control quantum systems. Migrating laboratory prototypes to field demonstrations often requires components or processes that are not yet available, such as specialized materials, fabrication facilities, integrated photonics, lasers, electronics, vacuum systems, interconnects, quantum control, and diagnostics. Unfortunately, many of these enabling technologies do not yet have a sufficiently large market to realize economies of scale. These obstacles delay the development of the required subsystems and create challenges to delivering functionality to end users without several iterations and subsequent refinements.

Discussion of Recommendation: Agencies that support engineering R&D should work with the SCQIS and its working groups to identify ways to facilitate the development of key components that are needed to make quantum sensors more compact, reliable, and cost-effective. Exploring joint efforts with industry and making targeted investments in infrastructure can produce cross-cutting, multi-functional components that enable several quantum devices, such as reliable lasers at applicable wavelengths and integrated optics circuits. Agencies should coordinate strategic R&D investments in these enabling technologies, to build joint ventures and talent that will foster a sustainable quantum industrial base.

A consortium or incubator that can manage small volume production runs (10 - 100 units) would fill a gap and provide infrastructure needed for rapid prototyping. There is also a demand for foundries that can produce integrated optics with new materials for chip-scale devices. A collaboration space for nanofabrication experts and non-experts to work together on designs would benefit this endeavor.

Compelling applications that justify dedicated engineering efforts can help to guide infrastructure development. In parallel, the QIST community can continue to leverage adaptable components that may be originally developed for other areas, e.g., photonics, microelectronics, or nanotechnology. Coordinating both of these approaches - versatile components for compelling applications - may present opportunities to seed QIST-related infrastructure in the broader marketplace, where economic motivations for maturing subsystem technologies can be stronger than what QIST applications alone might generate. Synergies among QIST and other technical sectors can provide mutual benefits.

Industry engagements can leverage appropriate partnerships through Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, centers of excellence, the NSF Innovation Corps programs, academic liaisons with industry, industry/university cooperative research centers, and national laboratories. Procurement, technology transfer, and connections with consortia such as the Quantum Economic Development Consortium (QED-C) can also improve the supply chain for components and enabling technologies.

Overcoming certain technical hurdles may require multiple agencies to agree upon, and work towards, shared long-term visions. Agencies should use the SCQIS and its working groups as a vehicle for program officers to share information and help bring technologies across the valley of death. Interagency coordination can help ensure continuity and persistence of R&D programs, as has been crucial for most of the successful quantum sensor exemplars. Appropriate budgets to support key science and engineering efforts should be planned. MOUs and MOAs can clarify roles and responsibilities. Realistic, evidence-based predictions of development schedules are important too, because patience is needed in order follow the arc of technology development.

Recommendation 4: Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.

Challenges Addressed: Some practices pertaining to intellectual property protection can impede or discourage cooperation, with these challenges becoming even greater for international engagements. Similarly, well-intended restrictions on procurement can delay acquisitions and slow development, in some cases reducing competitiveness. A balanced approach is therefore needed to ensure research security while maintaining the core values behind America's scientific leadership, including openness, transparency, honesty, equity, fair competition, objectivity, and democratic principles. While threats to research security are serious, there is also a risk that the overly broad implementation of protections could inhibit the flow of information that drives progress.

Discussion of Recommendation: Agencies should identify and implement helpful practices for resolving technology transfer issues such as source selection, purchasing authority, licensing agreements, and conflicts of interest. Efficient technology transfer and acquisition processes are vital for innovation. They can reduce administrative barriers for inventors to explore commercial viability, help end users access and co-develop products, and make public-private partnerships more straightforward. With public trust being paramount, ensuring that decisions are made in a manner that appropriately facilitates innovation and basic research, while reducing administrative burdens, can foster rapid innovation. To this end, agencies should thoughtfully consider their tolerance for technological or operational risks, while accounting for laws and norms, and maintaining research security best practices. As technology transfer depends on many people in different parts of government, the private sector, and academia, one approach is to engage the SCQIS, the NSTC Lab to Market Subcommittee, and their working groups to identify and share best practices.

Potential frameworks may include hybrid institutes and consortia that facilitate collaboration among entities, including those between government and private sector scientists. Start-ups and small businesses may benefit from standardized, possibly shared, government pre-approved mechanisms for handling a range of issues from intellectual property to immigration and investor relations. Advance market commitments for components or devices can incentivize early stage manufacturing of quantum technologies.[47] Other incentives may invoke government grants for user groups, shared infrastructure, or pre-competitive research to kick-start the development of enabling technologies. Agencies can engage with the SCQIS, consortia such as the QED-C, professional societies, and representative samples of institutions to identify best practices for facilitating technology transfer in these different venues.

International collaboration, which is important for growing the market and accelerating development, can be encouraged by relaxing barriers that discourage information sharing and preventing the creation of new barriers. Expediting international collaboration agreements, and improving guidance regarding the extent to which information sharing is permitted for items identified by the International Traffic and Arms Regulations (ITAR) and Export Administration Regulations (EAR) would facilitate work with international partners. Participation in international activities around standards, skills training, supply chains, and academic research can benefit all of the collaborating partners. These efforts must be balanced, though, to promote thriving innovation while protecting national security, intellectual property, and supply chains for critical and enabling technologies.

[47] 'Using advance market commitments for public purpose technology development,' https://www.belfercenter.org/sites/default/files/2021-06/UsingAdvanceMarketCommits.pdf

IV. Recommended Timelines and Metrics to Track Progress

To help implement these recommendations, some realistic expectations for the R&D community in the near-term (1-3 years) and medium term (3-8 years) are described. The SCQIS should create a venue to identify roles and responsibilities for agency participants in the following actions. It is incumbent upon the SCQIS, the agencies within the SCQIS, and the NQCO, in coordination with ESIX, to track progress, determine responsibilities, and create appropriate incentives to execute this timeline.

1-3 Years. In the next 1-3 years, community actions should include:

- Briefings and seminars on quantum sensors provided by QIST R&D leaders to various agencies. Surveys of available sensors and analysis of their impact on agency missions/needs should support these briefings. Ideally, these briefings will result in follow-up efforts to jointly test and demonstrate quantum sensors, as well as produce curated lists of existing and feasible performance metrics.
- Potential end users should engage with QIST-focused professional society meetings, workshops, and roundtables about their needs. End users could participate in proposers' day events to inform the R&D community about their interest in quantum technologies and desired performance metrics.
- Facilitate appropriate partnerships for new quantum sensor R&D on a rolling basis, to engage joint field tests and the evaluation of preliminary results. Acquisitions, demonstrations, and co-design of quantum sensors should help to pioneer and validate new applications. For tracking and assessment, it will be valuable to catalog existing and new joint R&D efforts on quantum sensors and their contributions toward maturing quantum sensing technologies.
- Identify specific, high-value applications for quantum sensors that can justify dedicated engineering and manufacturing efforts. One output would be prioritized lists of key components with specifications and plans for the associated engineering R&D.
- Identify and prioritize lists of engineering infrastructure and R&D activities that are needed to address gaps in enabling technologies and applications enabled by each activity. Estimate the time and investment required for each activity and its potential impact. Activities or infrastructure that will facilitate a broad set of quantum applications should be encouraged.
- Identify or establish bodies within agencies that can assist with the resolution of legal and policy issues in such a manner that facilitates quantum sensor technology development.
- Track engineering and scientific breakthroughs, as well as bibliometrics, participants, patents, licensing for quantum sensing technologies, and sales or revenue for quantum sensors, and track the key components or supporting technologies, both domestically and internationally.
- Project realistic resources required, including the supporting workforce, to implement the recommendations in this document.

3-8 Years. Once suitable technologies have been identified by coordinated activities, over the next 3-8 years, the R&D community and the agencies in the SCQIS should work to:

- Collaborate with end users to perform field tests and demonstrations that expedite early adoptions and transitions.
- Prioritize component miniaturization and subsystem integration.
- Develop and build R&D infrastructure through consortia and foundries.
- Develop standards for the identified quantum sensors and component technologies.

V. Summary

Quantum sensor development has a long and distinguished history within the United States and internationally. Quantum sensing technologies have already led to advances in fields such as: positioning, navigation, and timekeeping; remote sensing; biomedical, chemical, and materials sciences; and fundamental physics. Some successful examples required decades of careful investments, and a sometimes-circuitous series of theoretical and experimental developments, as well as sustained R&D efforts across multiple agencies and the private sector. The return on investment is evident from technologies, such as GPS and MRI, that are providing transformative impacts for society and advancing the frontiers of knowledge.

The realization of new quantum sensors is a tangible, near-term objective that should be catalyzed by agencies represented on the Subcommittee on QIS as part of the National Quantum Initiative program. Getting more quantum sensors to market is a goal that can lay a foundation for industries of the future and provide disruptive advantages for prosperity and security. Similar to the technological arcs described by the highlighted exemplars in Section II, these efforts will open new horizons and expand the reach of fundamental science and engineering.

An overarching strategy that engages several agencies, private sector entities, and academic leaders is important because there are potentially valuable quantum sensing technologies that are still vulnerable to failure. Opportunities can be missed for lack of communication between researchers and end users, underdeveloped supply chains, or insufficient engineering support for key components. Challenges also stem from barriers to technology transfer, tendencies to avoid risk, and the fact that timelines can be quite long to develop functional devices.

The four policy recommendations presented in Section III augment and expand upon the National Strategic Overview for QIS and provide specific approaches to overcome several of the main challenges facing quantum sensor developers. A concerted effort will help to identify mission-relevant quantum sensors, understand the performance requirements dictated by applications, anticipate fundamental limitations and failure modes for devices in realistic conditions, and take appropriate risks to explore truly revolutionary technologies. It will take leadership to facilitate collaborations between QIST R&D agencies and potential end users, and to identify appropriate budgets for these activities.

While there is much fundamental science to be done, and entirely new concepts and platforms for quantum sensors are likely to be discovered in the future, the strategy presented here has focused on joint efforts and field-testing of prototypes because these have been identified as gaps where coordination is needed and successes can bolster the entire field of QIST. Existing mechanisms that enable early-stage exploratory QIST research are an important source of new ideas and should not be supplanted by these recommendations. A national strategy to bring quantum sensors from lab to market must foster the long arc of technology development.

If this strategy is implemented successfully, joint efforts to develop, demonstrate, and utilize selected sensors should accelerate the dissemination of transformative products and services. First-mover advantages for early adopters and intellectual property for innovators and entrepreneurs will be gained along the way. Increased availability of quantum components and devices will benefit many users, including scientists in other fields, broadening the QIST R&D community. In sum, for the United States to realize the economic, security, and societal benefits of quantum technology, agencies should lead concerted efforts to bring the next wave of quantum sensors to fruition.

A Coordinated Approach to Quantum Networking Research

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

January 2021

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About the NSTC Subcommittee on Quantum Information Science

The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS) was legislated by the National Quantum Initiative Act and coordinates Federal research and development (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. More information on the SCQIS is available at https://www.quantum.gov.

About this Document

This document was developed by the SCQIS through its Quantum Networking Interagency Working Group. Recommendations in this report build on the *National Strategic Overview for Quantum Information Science* and identify pathways towards goals in *A Strategic Vision for America's Quantum Networks*. More information is available at https://www.quantum.gov.

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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force 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 for Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
LPS	National Security Agency Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NQI	National Quantum Initiative
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSpC	National Space Council
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
R&D	research and development
USPTO	United States Patent and Trade Office
USDA	United States Department of Agriculture
SCQIS	Subcommittee on Quantum Information Science
NQIAC	National Quantum Initiative Advisory Committee
NQCO	National Quantum Coordination Office
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QISE	Quantum Information Science and Engineering
QN	Quantum Network
QN-IWG	Quantum Networking Interagency Working Group

Executive Summary

Quantum networks (QNs) transmit quantum information between quantum devices and allow distribution of quantum entanglement, a physical resource known to be useful for quantum information processing. QNs in the form of internets or intranets enable larger quantum computations by connecting quantum computers together. Entangled sensor networks may enable precision metrology beyond what is possible with the best individual quantum sensors. Quantum properties can also be utilized to secure communication in novel ways. These promises of new science and technology motivate active research into creating and understanding QNs and their constituent components.

The fundamental applications, basic building blocks, and ultimate value propositions for QNs are still immature. Misunderstanding abounds. QNs cannot provide faster-than-light communication nor can QNs teleport material objects. Although research continues on secure forms of communication that are impervious to hacking by a quantum computer, there exist classical solutions—so-called post-quantum cryptography (PQC)—which are already in active development for deployment. For this reason, QNs are unlikely to replace today's internet directly.

Given the prospects of QNs to impact the Nation's economy, security, and innovation ecosystem, the United States must continue to invest in basic research to explore and exploit QNs while properly balancing investment decisions. Discovering and developing use cases is essential to maintaining leadership in this emerging area. Research to develop QN components and testbeds will also benefit quantum information science and engineering (QISE) broadly.

Recognizing the growing number of significant and sustained efforts on quantum networking research, the following technical and programmatic recommendations (TR and PR) identify actions Federal agencies can take together to advance the Nation's knowledge base and readiness to utilize QNs:

- TR 1: Continue Research on Use Cases for Quantum Networks
- TR 2: Prioritize Cross-Beneficial Core Components for Quantum Networks
- TR 3: Improve Classical Capabilities to Support Quantum Networks
- TR 4: Leverage "Right-Sized" Quantum Networking Testbeds
- PR 1: Increase Interagency Coordination on Quantum Networking R&D
- PR 2: Establish Timetables for Quantum Networking R&D Infrastructure
- PR 3: Facilitate International Cooperation on Quantum Networking R&D

A coordinated approach to quantum networking research that leverages the unique strengths of several Federal agencies will accelerate the science and engineering necessary to develop useful QN components and applications. As the complexity and scale of QN prototypes evolve, coordination is essential to establish the knowledge needed to explore quantum networking technologies and derive otherwise unattainable benefits.

In preparing the above recommendations, members of the NSTC Subcommittee on QIS and its interagency working group on quantum networking, representing various Federal agencies, are cognizant of the fact that each Federal agency has its own set of programmatic and budgetary guidelines and constraints. As such, these recommendations are meant to provide pathways to facilitate, further inform, and enhance each agency's approach to its own mission, to QISE in general, and to quantum networking research in particular. This was a primary goal of the members of the quantum networking interagency working group from the beginning of their deliberations to the drafting of the final report.

Introduction

Quantum mechanics enables capabilities beyond those that can be achieved with classical methods. Over the past century, harnessing quantum aspects of nature has produced essential technologies such as lasers, transistors, magnetic resonance spectroscopy, and atomic clocks. These technologies have tremendous impact on society, enabling today's internet, computers, medical imaging, and GPS navigation. Looking towards the future, the scientific and engineering community has shown that exploiting deeper, more esoteric properties of quantum mechanics, such as quantum superposition, entanglement, and measurement has profound implications for information processing, communications, remote sensing, and basic science, and may lead to a technological revolution. Past experience with disruptive advances suggests that applications envisioned today for quantum technologies may be dwarfed by not-yet-imagined discoveries that may be developed in industry, academia, and government labs in the United States and around the world. Early and sustained explorations that pioneer the application of these quantum properties will promote U.S. leadership in this emergent field and provide advantages for the Nation's economy, security, and innovation ecosystem.

A quantum network's greatest value comes from its ability to distribute entanglement. A unique property of quantum objects such as atoms or photons, entanglement is a fundamental physical resource for both probing scientific questions and for the development of advanced quantum information technologies. Perfectly entangled objects behave as a single quantum state regardless of how far apart they are and manifest correlations that cannot be obtained classically. Quantum networks provide a mechanism to coherently interconnect quantum devices so they work as a united quantum system, and can thus achieve goals that are impossible or impractical with classical technology.

Quantum networks will one day be able to distribute entanglement across several nodes that are composed of different quantum technologies, separated by a range of physical distances. Local quantum networks (intranets) may require diverse components such as quantum interconnects and quantum memories. Terrestrial quantum networks may include ground-, air-, and sea-based platforms. Some applications may benefit from satellites with quantum networking platforms in orbit. Most quantum protocols require support from a classical layer, so interfacing a quantum network with classical components will be critical. A fully functional network will require advancements in several enabling technologies such as sources, detectors, transducers, and repeaters for quantum states of light and matter. Cost-benefit determinations and decisions to develop particular technologies will depend on a deeper understanding of the underlying concepts of quantum systems and on the anticipated applications.

Cutting-edge Quantum Information Science and Engineering (QISE) research is needed in order to address the challenges of generating, distributing, and utilizing quantum entanglement. As summarized in *A Strategic Vision for America's Quantum Networks*[1] and the *Quantum Frontiers Report*[2], research efforts to develop foundational components, enable quantum state transduction, interconnect quantum devices, and explore new use cases for quantum networking are required. These efforts will produce new concepts and technologies in a diverse set of heterogeneous quantum systems and their interactions and catalyze progress in multiple disciplines, such as materials science, electrical

[1] https://www.whitehouse.gov/wp-content/uploads/2017/12/A-Strategic-Vision-for-Americas-Quantum-Networks-Feb-2020.pdf
[2] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf

engineering, quantum computing and metrology. Presently, the realm of quantum networking technology that remains to be explored is very large, and the field is in an exploratory phase of research and discovery.

Understanding Quantum Networking
The term *quantum networking* encompasses more than its most commonly known forerunner of quantum key distribution (QKD). QKD is a specific communications protocol that has stimulated research and development (R&D), but its value in real applications faces significant challenges[3]. Quantum networking is also quite different from post-quantum cryptography (PQC), which consists of classical algorithms operating on classical computers. As described by the National Institute of Standards and Technology (NIST), "The goal of post-quantum cryptography, also called quantum-resistant cryptography, is to develop cryptographic systems that are secure against both quantum and classical computers, and can interoperate with existing communications protocols and networks."[4] Post-quantum cryptography is critically important to protecting the Nation's communication infrastructure, and PQC-related standards, development, and deployment is underway. However, PQC is distinct from quantum networking research. Quantum networks enable applications beyond what is possible with purely classical methods, but they do not break the laws of physics. Quantum entanglement and the quantum networks that enable its distribution do not allow the transfer of information faster than the speed of light. And while quantum networks can teleport quantum information, the notion of teleporting material objects remains firmly in the realm of science fiction. As a final point of clarification, because quantum networks will likely perform vastly different tasks than classical networks, a quantum internet is not a replacement for the classical internet.

Examples of Quantum Networking Research Activities in the United States

The *Quantum Frontiers Report*[5] and the website www.quantum.gov[6] cite several dozen federally-funded QISE workshop reports relevant for quantum networking research. As an early example, the phrase *quantum internet* appeared in a 1999 QIS workshop and conference[7]. More recent research workshops devoted to quantum networking include the DOE ASCR workshop on quantum networks[8]; the NSF workshop on Quantum Interconnects[9]; the DOE Quantum Internet Blueprint Workshop report[10]; and the NASA-NIST workshop on space quantum communications and networks[11].

Investments by several U.S. agencies over three decades have seeded and developed the field of quantum networking. The variety of research programs funded by the civilian, defense, and intelligence funding agencies[12] illustrates how QISE and quantum networking research aligns with the missions of multiple agencies.

Department of Defense (DOD) has provided funding for quantum networking R&D for at least 25 years. A variety of Multidisciplinary University Research Initiatives (MURI) programs laid a foundation for quantum memories and quantum interconnects. The DARPA Quantum Information Science and

[3] https://www.nsa.gov/what-we-do/cybersecurity/quantum-key-distribution-qkd-and-quantum-cryptography-qc/
[4] https://csrc.nist.gov/projects/post-quantum-cryptography
[5] Ibid, https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[6] https://www.quantum.gov/
[7] https://nsf.gov/pubs/2000/nsf00101/nsf00101.htm; see also the 1999 Gordon conference on atomic physics
[8] https://info.ornl.gov/sites/publications/Files/Pub124247.pdf
[9] https://arxiv.org/ftp/arxiv/papers/1912/1912.06642.pdf
[10] https://www.energy.gov/sites/prod/files/2020/07/f76/QuantumWkshpRpt20FINAL_Nav_0.pdf
[11] https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings
[12] NQI Annual Report, *National Quantum Initiative Supplement to the President's FY 2021 Budget*

Technology (QuIST) program realized a QKD network demonstration[13] in 2007. Later, the DARPA QUINESS program explored long-distance quantum communication. The Army Research Laboratory (ARL) Center for Distributed Quantum Information program[14] focused on distributing entanglement beyond two nodes. Other current investments in quantum networking include the ARO Quantum Network Science MURI[15], AFOSR, ARO and ONR single investigator awards.

The Air Force Research Laboratory (AFRL) quantum networking research program focuses on a heterogeneous quantum network testbed to distribute entanglement across a multi-node network with both terrestrial- and space-based components. AFRL is also pursuing trapped ion and superconducting quantum bits (qubits) for memory, integrated photonics for information processing and transmission, and space-based optical channel development with both night and daytime operation. The AFRL testbed will include an open research component in the Innovare Advancement Center, applied research in AFRL laboratories, and test sites coordinated with multiple AFRL Technical Directorates.

Joint programs and cross-agency collaborations have advanced targeted sub-areas through sustained investments, for example with the DARPA Optical Radiation Cooling and Heating in Integrated Devices (ORCHID) and Quantum-Assisted Sensing and Readout (QuASAR) programs, and the Office of Naval Research (ONR) Quantum Optomechanics MURI and the Quantum Transduction MURI jointly supported by the Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO) and Laboratory for Physical Science (LPS). The LPS Cross Quantum Technology Systems (CQTS) program is another example of a program advancing critical component technologies, namely, high-fidelity qubit transduction. The Washington Metro Quantum Network Research Consortium[16] also provides an opportunity for cooperative research.

The National Institute of Standards and Technology (NIST) is developing a small, compact, and robust quantum repeater prototype. NIST also supports research to create a small 3-5 node heterogeneous quantum network[17] and to develop single photon detectors. A NASA-NIST workshop recently explored the possibility of space-based quantum communications demonstrations[9]. The National Science Foundation (NSF) QISE research portfolio includes the Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks[18], the Engineering Research Center for Quantum Networks[19], a program on Engineering Quantum Integrated Platforms for Quantum Communication[20], a program on Advancing Communication Quantum Information Research in Engineering[21], an Convergence Accelerator project titled, "Interconnecting Quantum Computers for the Next-Generation Internet," and quantum networking research in several NSF core programs[22] and center-scale efforts[23]. Department of Energy (DOE) National QIS Research Centers[24] and DOE Office of Science QIS programs[25]

[13] https://apps.dtic.mil/dtic/tr/fulltext/u2/a471450.pdf
[14] https://www.army.mil/article/227712/army_project_brings_quantum_internet_closer_to_reality
[15] https://www.arl.army.mil/wp-content/uploads/2020/02/arl-baa-005-FY-2021-W911NF20S0009-MURI.pdf
[16] https://www.nrl.navy.mil/news/releases/two-quantum-research-conferences-focus-navy-federal-collaboration
[17] https://science.osti.gov/-/media/nqiac/pdf/NIST_-presentation-NQIAC-20201027.pdf?la=en&hash=79A89EDF5BF6175360DF7EBCEB024F9B240B64A7
[18] https://nsf.gov/awardsearch/showAward?AWD_ID=2016136
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[20] https://nsf.gov/publications/pub_summ.jsp?ods_key=nsf18062
[21] https://nsf.gov/awardsearch/advancedSearchResult?Keyword=efri+AND+acquire
[22] https://www.nsf.gov/mps/quantum/quantum_research_at_nsf.jsp; https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505283
[23] https://www.quantum.gov/action/large-qis-efforts/
[24] https://science.osti.gov/Initiatives/QIS/QIS-Centers
[25] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages

support quantum networking research. Furthermore, the DOE recently announced A Blueprint for the Quantum Internet[26,27] and increased funding in Fiscal Year 2021 for quantum networking research[28].

No single agency can provide all of the approaches and capabilities that are required for accelerated progress in this field. Building on these activities and research programs will require increased coordination, as projects get more sophisticated and interconnected.

Challenges and Goals

The goal of creating functioning, adaptable, and scalable quantum networks to explore a growing range of scientific applications is a formidable endeavor. Quantum networking research requires multidisciplinary expertise and sustained, coordinated support from multiple agencies. Above all, the potential benefits to society to build a large quantum network versus the resources required to do so must be understood more fully.

In the near term (1 to 5 year timeframe), core components with benefits across multiple QISE areas are needed. These components include, but are not limited to, sources, detectors, interconnects, transducers, and repeaters. Sustained efforts over ten years may be needed for the development of more sophisticated platforms. These platforms may include novel materials and devices for quantum memory, testbeds of various scales, and satellite-based systems for space-based quantum network links. Additionally, sustained efforts may include the continued development of quantum algorithms and protocols optimized for quantum network architectures and applications.

The development of testbeds capable of distributing entanglement to heterogeneous subsystems (e.g., solid-state or atomic quantum computers, memory, and sensor nodes) is aligned with the missions of several agencies. Developing and operating prototypes, both large and small, can answer open questions about system-level behaviors, protocols, performance, and applications. Utilizing minimal, or “right-sized” testbeds, i.e., testbeds of minimum complexity or scope to answer the scientific and engineering questions in play, are a means to mitigate risk.

Entanglement distribution over long distances can support applications that differ from those addressed by short-range testbeds; both are important to pursue. Proposed applications for long distance quantum networking proving grounds include long-baseline interferometry, space-to-ground quantum networking for quantum communication, novel sensor arrays for fundamental physics or environmental monitoring, and enhanced navigation capabilities[29]. While these and other ideas need additional feasibility studies and rigorous research to develop, they illustrate the potential and challenges of large testbeds. As previously noted, QKD does not currently motivate the U.S. Government to build large quantum networks[30]; however, QKD can serve to validate the functionality of some subsystems (e.g., link budgets, timing, and detectors).

Exploring potential satellite-mission scenarios is stimulating research on applications and components suitable for space-based entanglement distribution. Given the long lead time to develop such infrastructure, exploratory efforts mitigate risk and will prepare the United States to engage swiftly if and when more strategic or compelling applications for space-based quantum networking emerge.

[26] https://www.energy.gov/articles/quantum-internet-future-here
[27] https://www.energy.gov/articles/us-department-energy-unveils-blueprint-quantum-internet-launch-future-quantum-internet
[28] https://www.energy.gov/sites/prod/files/2020/02/f71/doe-fy2021-budget-fact-sheet.pdf
[29] Ibid, https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings
[30] Ibid, https://www.nsa.gov/what-we-do/cybersecurity/quantum-key-distribution-qkd-and-quantum-cryptography-qc/

However, launching a full-scale mission entails significant costs. Therefore, synergistic efforts and interagency cooperation should be explored, and care should be taken so resource allocations for large-scale demonstrations do not negatively impact fundamental QISE studies with smaller testbeds. The approach of the United States to this scientific pursuit is not directed from the top, but rather is comprised of efforts spread across several agencies with different missions.

Mechanisms for Coordinating Quantum Networking Research

The National Quantum Initiative Act[31] calls for the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), with support from the National Quantum Coordination Office (NQCO), and advice from the National Quantum Initiative Advisory Committee (NQIAC), to coordinate QISE R&D efforts across the Federal government. The NQI program authorizes new QIS Research Centers and increases to core funding programs in quantum computing, quantum sensing, quantum networking, supporting technologies, and basic QISE. In addition, the NQI Act called on NIST to establish an industry consortium which is realized in the Quantum Economic Development Consortium (QED-C). Recognizing the need to facilitate coordination specifically on quantum networking R&D efforts, the SCQIS established the Quantum Networking Interagency Working Group (QN-IWG) in 2020 with representation from several agencies listed in the frontmatter of this report.

To promote U.S. leadership in this emerging field, priority should be placed on foundational science and engineering research that will underpin the development of future quantum networks. This prioritization is aligned with the National Quantum Initiative Act, the *National Strategic Overview for QIS*[32], and *A Strategic Vision for America's Quantum Networks*[33]. It is also consistent with input from the research community, summarized in the *Quantum Frontiers Report*[34]. Effective coordination will mitigate risk, accelerate progress, and position U.S. agencies to pioneer new quantum technologies in support of their missions.

Recommendations

The SCQIS, with input from the QN-IWG, has identified that coordination of basic R&D efforts to exploit quantum entanglement with quantum networks can accelerate breakthroughs in several QISE fields and will be a key enabling technology for future quantum information applications. The following technical and programmatic recommendations highlight critical steps that must be undertaken to accelerate U.S. leadership in quantum networking research.

Agencies should pool their knowledge to determine what minimal testbed functionalities are necessary to address the most pressing questions in quantum networking research. Cross-agency efforts that avoid redundant investments in costly infrastructure and pre-mature commitments to overly constrained approaches or modalities is part of the recommended strategy. Furthermore, to leverage test ranges and accelerate the discovery of valuable applications, coordinated efforts should increase the user base and provide access to a broad range of QISE and other research communities. Interagency coordination, from the bottom up, is therefore recommended to develop the tools and capabilities for quantum networking on all scales, motivated by the strategy of studying the fundamental science first.

[31] https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[32] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[33] https://www.quantum.gov/wp-content/uploads/2021/01/A-Strategic-Vision-for-Americas-Quantum-Networks-Feb-2020.pdf
[34] Ibid; https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf

Technical Recommendations (TR)

Four technical recommendations encourage continued research to explore applications, develop components, source supporting technologies, and leverage testbeds.

TR 1: Continue Research on Use Cases for Quantum Networks

Developing useful applications for quantum networks will require substantial and sustained basic research. Only a handful of anticipated use cases have been identified. More important, the cost and complexity of such quantum networks for specific applications are presently not fully known but are expected to be large. Fundamental limitations for quantum networks (or particular quantum network architectures) should be studied in order to understand and accurately guide the development of practical capabilities. This goal will require a combination of experimental and theoretical research on algorithms and protocols with consideration of feasible realizations. The United States must continue to invest in research on the potential advantages (and associated requirements) of quantum networks to justify future development.

TR 2: Prioritize Cross-Beneficial Core Components for Quantum Networks

Quantum networking requires unique components such as sources, detectors, memories, repeaters, transducers, and interconnects. Many of these quantum components are in an early stage of development and therefore require continued R&D in, for example, materials science, quantum optics, electrical engineering, fabrication, and quantum control. At this early stage it is impractical to choose a singular approach for a given class of components, or to select a particular subset of components to pursue, as different applications may require different functionalities and specifications. However, recognizing that some components will be valuable for multiple QISE sub-fields and even classical technologies, an initial focus on cross-beneficial modular components with a later expansion into development of more specialized components should yield the greatest benefit. The United States should prioritize increasing the technological readiness level of core components necessary for quantum networking with a coordinated approach to R&D efforts, including private sector opportunities such as via the QED-C.

TR 3: Improve Classical Capabilities to Support Quantum Networks

Quantum networks will require sophisticated support from classical technologies including communications, time-transfer protocols, photonics, electronics, and software. Advances in classical components and protocols can provide benefits not only for quantum networking research but for QISE studies more broadly. While the required performance attributes of supporting classical technologies will depend on the particular quantum protocols and applications to be implemented, the United States should continue to invest in the integration of classical approaches that are necessary to support the operation of quantum networks. Particular focus should be placed on methods that improve time and frequency information, expand quantum network throughput, and support networks of quantum sensors.

TR 4: Leverage "Right-Sized" Quantum Networking Testbeds

Quantum networking testbeds, demonstrators, and prototypes are crucial for guiding R&D. Flexible, reconfigurable, and adaptable testbeds are needed to explore scientific questions about quantum network behaviors and applications as the field evolves. This includes studies on how entanglement can be generated, transduced, stored, and swapped across multiple, heterogeneous nodes, and used for particular applications. Entanglement distribution over both short and long distances should be explored, as these entail different challenges and opportunities. To avoid premature spending on expensive efforts with limited adaptability, the United States should build "right-sized" quantum network testbeds to guide the development of quantum components and useful applications. At the same time, feasibility studies and exploratory research for long-distance test ranges—including satellite platforms—should continue, especially given the discovery potential and the long lead time for such infrastructure. Continued studies and analyses coupled with interagency coordination will reduce the likelihood of premature design choices and increase the scientific impacts, for example, by providing access to users from a broad range of QISE and other research communities.

Programmatic Recommendations (PR)

Coordination is vital for United States leadership in quantum networking research. Progress will require the capabilities and expertise of several agencies to ensure the requisite interoperability of components, testbeds, protocols, and applications. Three programmatic recommendations encourage continued and enhanced coordination, planning, and cooperation.

PR 1: Increase Interagency Coordination on Quantum Networking R&D

The broad scope and complexity of quantum networking R&D necessitates that agencies work together to maximize the return on government investment. Coordination at several levels will be essential: information sharing about R&D portfolios and plans; synchronized and complementary investments among agencies; and jointly funded and managed projects. Facilitation of this cooperation by the NQCO will ensure the early identification of best practices and gaps in the research portfolio, ultimately leading to accelerated progress.

PR 2: Establish Timetables for Quantum Networking R&D Infrastructure

Coordinated, interagency timetables for investment and expected capabilities should be developed, in accordance with published agency budgets, to avoid unnecessary delays and allow for long-term planning. Planning will engage stakeholders with long term research agendas and provide a forcing function to focus resources on the most promising and relevant component technologies. Understanding the triggers, dependencies, and gateways for useful quantum networking components, testbeds, and infrastructure will increase the impact of such investments on timeframes ranging from 5 to 20 years.

PR 3: Facilitate International Cooperation on Quantum Networking R&D

Promoting international cooperation with partners who adhere to the foundational principles of research integrity, such as openness, reciprocity, transparency, and merit-based competition fosters good-faith cooperation, accelerates the advance of fundamental science, and is particularly beneficial for quantum networking R&D. Because of the broad range of possible technologies and the unknowns in the application space, it is to the Nation's benefit to partner globally to explore the potential of quantum networks. As quantum networking technology develops, the United States must also participate in the establishment of standards and metrics for components and protocols, as appropriate.

Summary

The Subcommittee on Quantum Information Science recommends a coordinated approach to quantum networking research which leverages the strengths of multiple Federal agencies working together. The United States must understand the scientific and technological benefits and costs of quantum networks in computing, sensing, timing, and communications in order to justify and accelerate further development of this technology.

Four technical recommendations encourage continued research and development of quantum networking applications, components, and supporting technologies. Three programmatic recommendations emphasize the importance of continued and enhanced coordination among Federal agencies, identification of relevant timetables that streamline coordinated activities, and cooperation with international partners.

Quantum Frontiers
REPORT ON COMMUNITY INPUT TO THE NATION'S STRATEGY FOR QUANTUM INFORMATION SCIENCE

Product of

THE WHITE HOUSE

NATIONAL QUANTUM COORDINATION OFFICE

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INTRODUCTION

Under the Trump Administration, the United States has made American leadership in quantum information science (QIS) a critical priority for ensuring our Nation's long-term economic prosperity and national security. Harnessing the novel properties of quantum physics has the potential to yield transformative new technologies, such as quantum computers, quantum sensors, and quantum networks.

The United States has taken significant action to strengthen Federal investments in QIS research and development (R&D) and prepare a quantum-ready workforce. In 2018, the White House Office of Science and Technology Policy (OSTP) released the *National Strategic Overview for Quantum Information Science*, the U.S. national strategy for leadership in QIS. Following the strategy, President Trump signed the bipartisan National Quantum Initiative Act into law, which bolstered R&D spending and established the National Quantum Coordination Office (NQCO) to increase the coordination of quantum policy and investments across the Federal Government.

Building upon these efforts, the *Quantum Frontiers Report on Community Input to the Nation's Strategy for Quantum Information Science* outlines eight frontiers that contain core problems with fundamental questions confronting QIS today:

- Expanding Opportunities for Quantum Technologies to Benefit Society
- Building the Discipline of Quantum Engineering
- Targeting Materials Science for Quantum Technologies
- Exploring Quantum Mechanics through Quantum Simulations
- Harnessing Quantum Information Technology for Precision Measurements
- Generating and Distributing Quantum Entanglement for New Applications
- Characterizing and Mitigating Quantum Errors
- Understanding the Universe through Quantum Information

These frontier areas, identified by the QIS research community, are priorities for the government, private sector, and academia to explore in order to drive breakthrough R&D.

As background for this report, Federal agencies on the National Science and Technology Council Subcommittee on QIS have engaged with the QIS research community through public requests for information (RFI) [1] and through a series of QIS workshops, roundtables, and technical studies led by experts and stakeholders in the QIS R&D community. The NQCO analyzed the RFI responses and workshop readouts and found several recurring themes. This report summarizes and organizes the community input in order to focus the Nation's QIS research, academic, private sector, and Federal Government leaders on frontiers where key questions must be answered to enable the full potential of QIS. The Trump Administration remains committed to maintaining and strengthening America's QIS leadership and unleashing the promise of this emerging field to improve the prosperity, security, and well-being of the American people.

QUANTUM FRONTIERS IN BRIEF

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1. Expanding Opportunities for Quantum Technologies to Benefit Society

> ***"[W]hile the Strategic Overview takes a basic research-driven approach, applied research should not be neglected…it is important to accelerate the development of quantum technology toward usable results. This means balancing pure basic research with use-inspired research which is more likely to yield usable technology."*** *– RFI response*

The nature of information technology is governed by the rules of the universe itself, known as quantum mechanics. This realization helped establish the field of QIS. Presently, new technologies that harness unique quantum properties of coherence, entanglement, and measurement are emerging from fundamental advances in QIS. Developing practical, real-world applications for these technologies that benefit other scientists and end-users in a wide range of disciplines is now an important frontier for quantum information scientists and technologists. Two major areas of inquiry are key for making progress along this frontier: discovering what is fundamentally possible with quantum technology, including practical quantum advantages and a deeper understanding of the classical-quantum trade space; and engaging interdisciplinary QIS researchers with domain scientists and end-users early on, to work together and identify potential applications for QIS technologies and concepts in government, industry and other branches of science.

a. Elucidating Fundamental Capabilities of Quantum Technologies

Improving our fundamental understanding of how quantum technologies can provide meaningful advantages over conventional classical methods was a recurring theme in RFI responses. This includes: elucidating where improvements can be gained over existing technologies by utilizing quantum phenomena to accomplish specific tasks; characterizing entirely new capabilities enabled by quantum phenomena that have no classical counterparts; and understanding fundamental advantages for quantum metrology and quantum computing that can be derived from quantum networking.

For quantum computing, RFI respondents noted that advances in computational complexity theory could clarify the classes of problems for which quantum computational advantage is possible in principle, paving the way for building more useful quantum algorithms in the long term. In the near term, consideration of non-asymptotic regimes (corresponding to problem sizes that could be addressed by near-term digital quantum computers or simulators) and specific device parameters (e.g., actual time requirements for quantum gate operations and auxiliary tasks such as stabilization or error-correction protocols) will also be important for such analyses. The development of approaches for mathematically evaluating the potential for quantum advantage in analog quantum computation (quantum annealing, adiabatic quantum computation, and quantum emulation) is also an area for exploration.

> ***"Quantum complexity theory research should be encouraged to understand where quantum computing has the most value and why. Quantum algorithm research should focus on demonstrating incontrovertible quantum advantage on real quantum hardware for classically-intractable practical problems."*** *– RFI response*

RFI respondents also highlighted the potential value of heuristic approaches for finding applications of near-term quantum devices. Direct experimentation with quantum devices could establish what they are capable of in practice; applications for established quantum capabilities may then be sought.

> ***"The space to be explored in the next 10 years is vast and the first useful applications of these new technologies may come from actually just trying new ideas without requiring a long and slow period of developing the appropriate theoretical foundations."*** *– RFI response*

Members of the research community have also recognized the potential for demonstrating quantum advantage on noisy, intermediate-scale quantum (NISQ) devices. Near-term quantum computers and quantum emulators could be explored to realize transformative approaches with advantages for working on problems that can be mapped to a quantum algorithm or to a quantum system for computation or simulation. Developing new quantum algorithms suited to NISQ devices, and formal methods of resource estimation for evaluating their potential for quantum advantage, could facilitate near-term progress in this frontier.

> ***"Applications for NISQ computing are critical for the future of QIS because, in addition to the scientific insights they generate, they form the path to the longer term goal of fault tolerant quantum computation."*** *– RFI response*
>
> ***"What are the NISQ-era algorithms that offer quantum advantage for meaningful problems?"*** *– RFI response*

b. Engaging QIS Researchers with Domain Specialists and End-Users

The need to identify important real-world tasks for which quantum technologies may offer a promising solution was a common theme in the RFI responses. Prospective areas for exploration include biocompatible quantum sensors for in vivo characterization of biomolecules for diagnostic or research purposes; QIS-based metrology for environmental or industrial systems monitoring; quantum computing approaches to classically-hard problems such as modeling of chemical systems relevant to drug discovery or nitrogen fixation, and certain optimization and machine learning tasks; quantum networks to enable secure communications and blind quantum computation in support of data privacy and confidentiality; deployment of quantum networking for satellite communications; and further development and deployment of robust quantum-enabled navigation systems.

> ***"[Identify] key problems that need QIS as a tool for solutions, from modeling and understanding complex physical phenomena to optimization problems to cryptography and security; characterizing problems and their quantum requirements."*** – RFI response

RFI responses also noted that efforts to find meaningful applications for quantum technologies would be accelerated by connecting QIS scientists and engineers with experts from other domains to explore potential use cases. This could expedite the timeline for finding new solutions to critical societal challenges and enable informed technology design strategies from an early stage. Reciprocally, as an added benefit, this work would provide a new lens through which to advance fundamental QIS by motivating new experiments, stimulating new hypotheses, and inspiring theoretical advances. Collaboration and continued discussion across QIS, computing, mathematics, engineering, and other application domains will be needed to reveal what can—and cannot—be accomplished uniquely with quantum technologies, and to achieve this potential in actual devices.

> ***"In a co-design approach, the problems can help drive the design and the engineering and scientific research while at the same time the scientific and engineering advances can drive designs to motivate new approaches to solving problems."***
>
> *– RFI response*

An overarching goal for R&D in this frontier is to demonstrate quantum technologies that offer advantages for practical tasks. How might quantum technologies bring better, cheaper, or never-before-possible solutions to other scientists and end-users, and to society at large? Discoveries in this area would help to further establish the value proposition of QIS, beyond its role in expanding the boundaries of human knowledge.

2. Building the Discipline of Quantum Engineering

"Quantum engineering should be established as a new discipline or a sub-discipline in engineering schools which requires developing curricula and textbooks both at undergraduate and graduate levels." *– RFI response*

"As new quantum information science-based technology ('quantum technology' for short) develops, the U.S. will need a new type of profession that has not previously existed: the quantum engineer. Quantum engineers will not be—and will not need to be—specialists in the detailed physics of QIS but will instead be expert in the use and extended application of the new systems, tools and possibilities enabled by QIS." *– RFI response*

"One element to U.S. Government engagement with academia on workforce development should be promoting the development of the field of quantum engineering, not as classical engineering to support quantum technologies (i.e. classical control electronics or thermal control systems), but as its own discipline where there are models of abstraction permitting useful engineering of quantum systems…quantum-engineering-focused research efforts will be required for developing the engineering models that appropriately abstract away the details of the complex underlying effects, while still allowing academic courses that teach these models to provide engineers with the appropriate intuition and depth of understanding." *– RFI response*

Advances in QIS and technology have led to compelling proof-of-principle experiments with gate-based and analog quantum computing, and demonstrations of quantum sensing with unprecedented capabilities and precision. However, many technical and systems-level challenges still remain to be overcome before today's quantum control capabilities are considered as standard ingredients for planning and constructing complex devices. This is especially true for products defined by a broad range of specifications and practical constraints for real-world applications. The emerging discipline of quantum engineering may bridge this gap by creating new perspectives on topics ranging from designing and integrating components, to optimizing and verifying functionality, and providing useful abstractions and heuristics. As illustrated by some RFI responses, these are among the variety of concepts currently referred to as quantum engineering. Pathways for progress in this frontier include: understanding what makes designs scalable and useful; integrating the development of quantum hardware, software, and support technologies; developing and using system-level architectures; and creating the new discipline of quantum engineering.

a. Integrating Quantum Hardware, Software, and Support Technology

Physical elements that were identified in several RFI responses and workshop reports as needing to be characterized, integrated, and optimized by quantum engineers include qubit arrays, refrigeration devices, electronics, optics such as silicon nitride waveguides and delay lines, single-photon detectors, vacuum systems, wiring and feedthroughs, lasers and stabilization components, radiofrequency and microwave technologies, and device packaging. Other hardware research areas that RFI responses suggested may be improved and integrated with an engineering approach are: the development of quantum memory technologies; efficient methods of quantum state preparation—especially for loading classical data into quantum information storage, processing, or communication devices; and the transduction of quantum states between heterogeneous components of quantum systems.

On the software and systems side, important research areas identified in RFI responses include development of modular software designs, methods for mapping computational problems to the specific hardware configurations of early devices, and exploration of programming languages built upon hardware-informed semantic models. Major research opportunities include further development of system architectures and abstractions and community-acceptable metrics and standards (once technologies have reached the appropriate level of maturity) for use in system validation, verification, and performance benchmarking and to inform technology selection and system optimization for specific use cases.

"Whether it be in quantum computing, quantum software, or other QIS disciplines, a hybrid approach that integrates various quantum systems will be important to make breakthroughs. This means facilitating the combination of the best of various quantum systems to build new devices, capabilities, and platforms based on multiple different physical realizations." *– RFI response*

"Longer term, the use of abstractions to enhance productivity will be needed, once quantum resources are more plentiful….We must establish the sorts of modularity and layering commonly needed for scalable systems."

– Next Steps in Quantum Computing: Computer Science's Role (Computing Community Consortium 2018)

b. Exploring System-level Architectures, Abstractions, and Testing

Establishing essential principles of quantum engineering that enable researchers to build and use quantum systems at various levels of abstraction without having to start from first principles is considered groundbreaking for QIS R&D. Research community members also suggested that quantum engineers should work closely with domain experts to pioneer new applications that drive the design and experimental testing of tools, techniques, and architectures, and which could lead to near-term use cases for quantum technologies, as noted for frontier A.

"[W]e have found the most fruitful work results from programs that enable close collaborations between quantum engineers and application domain experts."

– RFI response

c. Enabling Modular Systems

At the hardware level, systems of tens of entangled qubits have been demonstrated experimentally for several different qubit types, including superconducting, trapped ion, and photonic as examples provided in the RFI responses. These experiments illustrate that it is possible to access unique regimes for quantum information processing. However, as they grow in number, qubit systems generally become increasingly difficult to prepare, couple, and control, and their inherent complexity makes them concomitantly more difficult to understand, model, and validate—posing significant challenges for realizing systems of a larger scale. RFI responses highlighted the need to develop techniques, protocols, models, and validation approaches to enable heterogeneous, modular, and scalable designs, fabrication methods, characterization techniques, and packaging of qubit technologies.

> ***"Developing common terminology and metrics will allow researchers in different groups to communicate more clearly and encourage better exchange of ideas and enable faster progress."*** *– RFI response*
>
> ***"Several QIS areas remain in an early phase of research, where the engineering of a core technology is relatively immature."*** *– RFI response*

Members of the R&D community identified a range of technical challenges that would benefit from the application of engineering principles, including: optimizing quantum materials, fabrication, and manufacturing methods to meet hardware requirements; establishing specifications, parameters, and a common terminology for quantum system design that can be shared across qubit technologies and disciplines; developing new models of system behavior and efficient emulation techniques for comparison with actual performance; inter-qubit communication and connectivity; and methods for debugging systems that do not perform as intended. These methods could enable design and development of stable, self-contained collections of physical quantum hardware and control systems that would serve as the basis for a modular approach to system design.

> ***"Focus on how to build quantum computers with a modular architecture. This will require bringing together [experts] from engineering, as well as system architects and computer scientists, to think about how to make interfaces and how to scale those interfaces."*** *– RFI response*

A vision of progress in this frontier is to build a broadly applicable set of quantum engineering principles, tools, and specifications for designing quantum systems that are stable, sophisticated, compact, and cost-effective enough to be useful and usable in a range of different environments and contexts. They would also lay the groundwork for designing and deploying large-scale, quantum computing and communication technologies and infrastructures.

3. Targeting Materials Science for Quantum Technologies

> ***"In applications of quantum computing, qubit quality is inextricably tied to materials quality, particularly in solid-state platforms. The longer coherence times and lower error rates needed to advance the aims of error-corrected quantum computing will come fastest through a full predictive capacity for materials performance, one that is able to guide fabrication well enough to deliver desired QIS characteristics with consistency and without trial-and-error processes. An improved understanding of materials might also uncover new or better ways to fabricate error-protected qubits, which if found and made reliably could represent a transformative leap toward logical-qubit creation."*** *– RFI response*

Quantum information can be coded into different physical systems: ions, atoms molecules, or solid-state materials and superconducting circuits, and photons or phonons—each with its own advantages and challenges. Coherence in each system generally depends on how the qubits and interconnections are fabricated and controlled. Fundamental knowledge of the quantum properties of matter can inform the design of high-fidelity qubit systems to minimize the potential for noise and error. Developing and applying new and precise methods for characterizing and fabricating these physical components according to engineering specifications will accelerate advances in system development. Key areas ripe for progress include: using materials science to improve device performance, and pursuing new approaches to materials design, fabrication, and characterization.

> ***"Research opportunities encompass (1) development of new in situ and in operando characterization and feedback techniques to discover materials with improved properties and functionalities; (2) characterization and control of quantum material properties on all length and time scales relevant to function, including tools to reveal the often subtle forms of emergent and topological order; and (3) prediction of the fundamental properties of quantum materials, including emergent order, behavior far from equilibrium, and functionality in the presence of disorder."***
>
> *– Basic Research Needs Workshop on Quantum Materials for Energy Relevant Technology (DOE 2016)*

a. Using Materials Science to Improve Device Performance

RFI respondents identified key opportunities for communication and collaboration between QIS researchers and those in fields such as materials science, chemistry, and condensed matter physics to leverage current knowledge and tools for improving the quality and resilience of the materials currently in demand for building quantum devices. Established theory and experimental techniques from these fields will aid in the design, characterization, fabrication, and evaluation of improved near-term devices. Building a robust approach for mapping materials characterization knowledge to estimated quantum bit and quantum device performance will advance this frontier.

> ***"[D]evelop and optimize new advanced materials, including solid-state hosts for atom-like qubits (e.g., diamond and other semiconductors), materials with emergent properties (analogous to graphene and topological insulators), and materials developed by learning lessons from evolved (natural) biological and chemical materials."***
>
> *– Quantum Sensors at the Intersection of Fundamental Science, Quantum Information Science, & Computing*

b. Pursuing New Approaches to Materials Design, Fabrication, and Characterization

Members of the research community noted the opportunity to build on existing knowledge to advance the theories, tools, and techniques that will enable researchers to explore the fundamental quantum nature of materials, predict material properties, devise new synthesis and integration processes, and target new kinds of materials to outperform those currently in use. Key research pathways include exploration of artificial intelligence-driven materials science; improved chemical simulation techniques; 3-D atomic-scale imaging; scanning probe techniques for quantum materials characterization and quantum device readout; higher-sensitivity magnetic resonance tools; and other new measurement and modeling capabilities suited to extreme conditions.

> ***"Quantum device coherence times, gate fidelity, and other metrics must be improved using new materials, processes, designs, and approaches. Goals for device improvement should be tied to actual system performance needs based on the best system estimates possible."*** *– RFI response*

Researchers noted that progress in realizing topological materials could yield entirely new, inherently error-protected qubits that are expected to be much more resilient to noise than approaches currently deployed. This area of exploration will involve substantial challenges in realizing quantum information primitives in such systems, beyond the initial difficulties of showcasing topological behavior in such materials in the first place. Demonstration of topological protection of quantum information in materials remains a wide-open question, with many potential pathways for success.

Opportunities were also highlighted for coupling a deeper understanding of materials properties with higher-resolution, more precise, and more easily scalable fabrication and manufacturing processes to enhance the ease with which materials can be customized, including fabrication techniques to enable the bottom-up construction of qubits from the atomic or molecular components. Collaboration between quantum engineers and those studying materials science would enable the development of models for optimizing materials selection for desired function and performance based upon controllable properties, such as density of states, tunneling energies, and resonance frequencies, and the qubit-relevant characterization of materials-related decoherence mechanisms.

"How can we develop a fast, iterative synthesis technology that integrates in situ fabrication and characterization and is informed and/or directed by first principles theory and machine learning, thereby enabling rapid convergence toward a desired quantum-coherent property[?]"

– Opportunities for Basic Research for Next-Generation Quantum Systems (Basic Energy Sciences Roundtable, DOE 2017)

Progress in this frontier has the potential to enhance researchers' abilities to fabricate high-quality qubits and other specialized materials for quantum device components reliably and according to desired specifications, by design. It could also spur progress towards next-generation quantum materials with increased resilience to noise, supporting efforts to build stable, compact, and low-cost quantum devices with the potential for practical deployment.

4. Exploring Quantum Mechanics through Quantum Simulations

"The intellectual roots of [quantum computing] go back decades to pioneers such as Richard Feynman who considered the fundamental difficulty of simulating quantum systems and 'turned the problem around' by proposing to use quantum mechanics itself as a basis for implementing a new kind of computer capable of solving such problems. Although the basic theoretical underpinning of [quantum computing] has been around for some time, it took until the past 5 years to bring the field to an inflection point: now small and intermediate-scale machines are being built in various labs, in academia and industry."

– Next Steps in Quantum Computing: Computer Science's Role (Computing Community Consortium 2018)

Engineered quantum technologies can be used to efficiently simulate and emulate intrinsically quantum systems to elucidate their properties. Such efforts have already improved our understanding of previously mysterious phenomena and have the potential to lead to stunning progress in foundational and applied science. Quantum information technologies, such as NISQ computers and analog quantum simulators available over the next 5 years, will offer the chance to improve our understanding of quantum systems through computation, simulation, experimentation, and other studies. Key areas for progress include: leveraging quantum devices to improve approaches for the classical, quantum, and hybrid simulation of quantum behavior from many-body physics to chemistry to materials science; demonstrating quantum advantages based on quantum simulation; and developing new algorithms for NISQ-era devices, and exploring their performance in the presence of noise.

"A quantum, rather than classical, simulation is naturally better equipped to explore the state space spanned by quantum systems."

– Quantum Computing: Progress and Prospects (National Academies of Sciences, Engineering, and Medicine 2019)

a. Developing Quantum Simulation Applications

Many researchers noted the potential for quantum devices to improve our understanding of the science and engineering of a range of quantum systems. Key areas of opportunity include: chemical electronic structure calculations; nuclear vibration and rotation calculations for molecular spectroscopy; many-body chemical dynamics and chemical reactions; equilibrium properties, phase diagrams, and other materials properties; and other many-body dynamics and complex physical phenomena such as protein folding, high-temperature superconductivity, or nuclear fission. Simulation of these systems could be conducted via analog or gate-based quantum computers, quantum emulation, or simulations run on classical computers.

"[T]he answer to the question whether quantum mechanical resources of a quantum computer are required for accurate computation of molecular electronic properties is then also highly relevant. If the answer is affirmative, then this makes a perfect practical case for quantum computing. Otherwise, if we can show that quantum chemistry may be described classically in spite of its quantum nature, this can open the door to efficient exact solutions of these problems on a classical computer….Regardless of which way the question is resolved, the chemistry community stands to benefit, gaining a tool for simulating the electronic structure of molecules." *– Quantum Information and Computation for Chemistry (NSF 2016)*

b. Implementing Algorithms on Available Devices and Exploring Their Performance

This frontier also reflects the opportunities to advance and implement quantum algorithms and protocols for studying these and other quantum systems. Examples of quantum algorithms highlighted by the research community include quantum phase estimation, adiabatic state preparation, quantum imaginary time evolution, Hamiltonian simulation, real space simulation, and fermionic simulation. Hybrid quantum-classical approaches, which leverage quantum hardware for specific computational steps within a larger algorithm, include the variational quantum eigensolver (VQE) for ground-state energy optimization and the quantum approximate optimization algorithm (QAOA). A key element of this work will be establishing performance benchmarks for comparing different algorithms—both theoretically and empirically—and for comparing quantum algorithm outputs to the best-known classical results. Insights gleaned from this work could also inform new or improved classical computational approaches, helping to establish their capabilities and limitations.

"It is clear that one will rely on hybrid quantum-classical algorithms for many years to come, and there remain many open questions. One is how to best adapt quantum algorithms within existing quantum-classical frameworks."

– Enabling the Quantum Leap: Quantum Algorithms for Chemistry and Materials (NSF 2019)

This specific use case of NISQ devices provides a promising context to study how noise affects algorithm implementation, varies with different hardware configurations, and scales with system size. Research would benefit from empirically validated resource estimation strategies and the development of noise models in support of system validation—perhaps enabled by quantum and approximate circuit simulators. Quantum and classical simulation methods could also be used to model and optimize other quantum technology components, such as elements of quantum networks.

> ***"Estimating resources for quantum algorithms using realistic quantum computing architectures is an important near-term challenge. Here, the focus is generally on reducing the gate count and quantum circuit depth to avoid errors from qubit decoherence or slow drifts in the qubit control system. Different types of quantum hardware support different gate sets and connectivity, and native operations are often more flexible than fault-tolerant gate sets for certain algorithms. This optimizing of specific algorithms to specific hardware is the highest and most important level of quantum computer co-design."***
>
> *– Quantum Computer Systems for Scientific Discovery (NSF 2019)*

A vision for this frontier is to demonstrate transformative quantum advantage for solving many-body quantum physics, quantum chemistry, or materials science problems, while improving researchers' abilities to engineer quantum hardware and software. It could also lead to models for how best to leverage quantum and classical computing resources complementarily for different kinds of problems. At a fundamental level, it will help to illuminate practical efficiency, accuracy, and precision limits of various methods for the computational study of quantum systems.

5. Harnessing Quantum Information Technology for Precision Measurements

> ***"State-of-the-art detectors and sensing are developed and employed to perform precision measurements that probe the laws of nature, to discover new particles and states of matter, and to develop capabilities for national security needs."***
>
> *– Nuclear Physics and Quantum Information (Nuclear Science Advisory Committee, DOE, NSF 2019)*

Several cutting-edge metrology techniques already demonstrate key benefits from quantum control and QIS-related approaches, including atomic clocks, atom interferometers, magnetometers, and nuclear magnetic resonance (NMR) imaging systems. In this frontier, there are opportunities to improve precision and accuracy, develop new measurement modalities, improve methods for deploying these technologies in the field, and pioneer new applications for precision measurements. Key areas for exploration include: improving understanding of quantum-related limits to accuracy and precision for systems that can be deployed in the field to enhance navigation capabilities and for realization of standards; new modalities and applications for quantum sensing in situ and in vivo; and using entanglement and small-scale quantum computers to improve measurement technologies.

> ***"Attaining strong quantum enhancements in detection (e.g., quantum illumination) and in sub-Rayleigh quantum imaging represent significant challenges. Equally important is the construction of compact and robust quantum sensors, detectors, and imagers that are suitable for deployment in extreme environments."***
>
> *– Future Directions of Quantum Information Processing. A Workshop on the Emerging Science and Technology of Quantum Computation, Communication, and Measurement (Virginia Tech Applied Research Consortium, DOD 2016)*

a. Deploying Quantum Technology for Improved Accuracy and Precision

Precision position, navigation and timing (PNT) applications already use quantum technology, but typically have practical constraints on size, weight, power and cost (SWAP-C). Bandwidth and reliability also matter. Members of the R&D community highlighted the exploration of attaining superior performance while satisfying overall package requirements as a critical direction that combines measurement science with quantum engineering. Positioning with millimeter accuracy and time-transfer with sub-nanosecond accuracy are available in the laboratory. However, their transition to practical quantum technologies, including designing and manufacturing rugged components for practical deployment, remains a challenge.

The entire set of System International (SI) units is now tied to constants that can be realized using quantum phenomena. This was a key reason for the redefinition of the kilogram in 2019. Connecting measurements in the field and on the factory floor directly to fundamental constants, by using QIS technology is a capability that will affect many fields of science and technology. New procedures can replace some time-consuming and elaborate calibration chains that were required for conventional approaches to metrology. This frontier will also leverage QIS to enable better precision and accuracy.

> ***"There are many laboratory demonstrations of quantum sensors with performance eclipsing fielded instruments, presenting opportunities for significant return on investment for engineering/development….Clocks, accelerometers, and magnetometers may be the best opportunities."***
>
> *– Applications of Quantum Technologies (Defense Science Board, DOD 2019)*

b. Creating New Modalities and Applications for Quantum Sensing In Situ and In Vivo

While quantum advantages for sensing can be profound, part of this frontier entails identifying compelling use-cases that justify such quantum control as opposed to simply increasing flux or system size in standard approaches. Community-identified opportunities for exploration of precision measurements include high energy physics detectors; spectroscopy in chemistry labs; NMR techniques that combine cutting-edge spatial resolution with spectroscopic chemical shift sensitivities; geodesy and mapping; hydrology and mineral exploration; astronomy with quantum-enhanced telescopes; and a variety of bio-science applications ranging from electroencephalography (EEG) and magnetoencephalography (MEG) to studies of vision, photosynthesis, cellular dynamics, and magnetotaxis.

> ***"[H]ighly entangled systems of trapped ions can be used not only for quantum simulation…squeezing can perform extraordinarily precise measurements of force, with implications for searches of ultralight dark matter. Measurement of forces and fields is a basic operation of precision measurement and tests of fundamental symmetries, and some of the most exciting developments today take advantage of QIS techniques."***
>
> *– Opportunities for Nuclear Physics and Quantum Information Science (DOE 2019)*

Researchers also recognized that new measurement modalities with quantum states of light, next generation atomic clocks, ultracold molecules, matterwave interferometers, color centers in crystals, and other systems, offer new capabilities and in some cases unprecedented precision and accuracy based on quantum coherence and superposition. However, to push this frontier even further, demonstrating the clear advantages for metrology using *entanglement* and many-body quantum states with non-classical correlations is seen as an important next step. Using squeezed vacuum states for Advanced LIGO is a major achievement in this direction. Exploring this frontier will enable improved performance with increasing degrees of entanglement, for useful applications in other scientific fields.

> ***"[S]cientists have created new opportunities for understanding and constructing quantum matter where many-body physics is no longer feared as a hurdle for precision measurement, but rather a new frontier to advance precision and accuracy."***

> *– Manipulating Quantum Systems: An Assessment of Atomic, Molecular, and Optical Physics in the United States (National Academies of Sciences, Engineering, and Medicine 2020)*

c. Using Entanglement and Quantum Computers to Improve Measurements

Extending this concept to sensor arrays and other networked quantum systems (e.g., a network of entangled clocks) was identified by the research community as a cutting-edge opportunity for quantum metrology. In principle, optimal entanglement and measurement using quantum pre- and post-processing enable new domains of metrology. One suggested direction to explore is to use many-body quantum states, prepared with quantum circuits or small-scale quantum processors, to enable metrology. This would utilize cutting-edge QIS technologies to expand the precision measurement frontier.

> ***"[Q]uantum technology is already having an impact in metrology and fundamental discovery (gravitational waves; LIGO). Five years is a very realistic timeframe for demonstrating the usefulness of quantum sensing technology in particular."***
>
> *– RFI response*

Progress in this frontier could lead to deployment of quantum sensors in new contexts and scientific domains. These devices are expected to push the limits of accuracy and precision, and to be realized via new underlying sensing mechanisms. In PNT, quantum technologies are likely to enable new levels of accuracy and time transfer capabilities in field campaigns. In metrology, quantum effects can be used to disseminate standards tied to defined SI units. Deployment of novel quantum sensing technologies is a major goal, as is identification of key use cases where entanglement and small quantum computers can improve metrological outcomes in applied settings.

6. Generating and Distributing Quantum Entanglement for New Applications

> ***"[O]nly a small number of scientific techniques and technological applications take advantage of the unique phenomena of quantum superposition and entanglement."***
>
> *– Opportunities for Basic Research for Next-Generation Quantum Systems (Basic Energy Sciences Roundtable, DOE 2017)*

Progress in distributing entanglement has stimulated great interest in quantum networks as an enabling platform for quantum technologies. Interconnecting quantum devices by entangling qubits in separate modules may be a key pathway for scaling up quantum computers. Furthermore, distributing quantum information across spatially separated nodes is expanding the intellectual domain of quantum communication into the larger field of *quantum networking*. Inventing the physical layer components to distribute entanglement, developing algorithms, applications, protocols, and use cases for various quantum network systems, and understanding the integration of components and protocols into systems-level architectures are areas to explore in this frontier.

> ***"Quantum communication systems require repeaters and quantum memory…early technology demonstrations exist but repeaters and memory are far from levels of performance to be useful."*** *– RFI response*

a. Developing Foundational Components for Quantum Networks

RFI respondents and workshop reports named several foundational technologies that need further development before long-distance quantum networks can be realized. These range from quantum repeaters to memories and interconnects. An outstanding challenge is the development of quantum repeaters that are efficient and scalable, possess sufficient bandwidth, and are deployable. Likewise, plug and play modules for quantum memory remain an open R&D track, despite early progress on protocols.

> ***"Quantum interconnects (QuICs) present special challenges, as they must allow the transfer of fragile quantum states between different physical parts or degrees of freedom of the system. The diversity of QIT [quantum information technology] platforms (superconducting, atomic, solid-state color center, optical, etc.) that will form a 'quantum internet' poses additional challenges. As quantum systems scale to larger size, the quantum interconnect bottleneck is imminent, and is emerging as a grand challenge for QIT."***
>
> *– Development of Quantum InterConnects for Next-Generation Information Technologies (NSF 2019)*

b. Enabling Quantum State Transduction

Quantum interconnects are needed for coupling the often heterogeneous elements of quantum systems. Researcher-identified avenues for exploration include: coherent transduction of quantum states in atomic, optical, microwave, electronic, and solid state systems; quantum frequency conversion; quantum control of spin states, charge states, polarization, spatial modes, orbital angular momentum, and other degrees of freedom such as spectral-temporal encoding; higher dimensional qubits; and manifestations of entanglement with continuous variables. Furthermore, practical methods to generate and distribute entanglement must mitigate loss, noise, and errors to meet specifications (e.g., data processing rates and compounded efficiency or throughput) needed for applications such as those discussed below.

> ***"[L]arge-scale networks of superconducting quantum computers—quantum networks—are impossible without new ways to distribute entanglement over long distances, necessitating the development of efficient quantum state transduction."*** *– RFI response*

c. Integrating Quantum Networking Systems

Researchers have identified a need for infrastructure and engineering to facilitate entanglement distribution over a range of distance scales. Entanglement distribution over short ranges, from cryostat to cryostat, across integrated photonics devices, or between qubits in a single system are key challenges. Aerial and satellite platforms equipped for free-space communication of quantum states and for interconnecting local networks (e.g., terrestrial fiber-optics based quantum intranets) are also pursued in this frontier. Infrastructure and protocols for entanglement distribution and research testbeds or facilities (e.g., with switching, purification, interconnections, and hybrid classical-plus-quantum methods) require substantial exploration.

> ***"[O]ptical telescopes connected across the globe in a quantum network could allow determination of apparent positions of stars with unprecedented precision. Evolution of the above ideas will depend very much on theoretical efforts to develop concepts of experiments and to evaluate their sensitivity."***
>
> *– Quantum Networks for Open Science Workshop (DOE/ASCR 2019)*

d. Exploring Quantum Networking Algorithms, Applications, Protocols, and Approaches

Members of the R&D community also pointed beyond the physical layer, towards opportunities to explore applications of quantum networks such as distributed quantum computing, blind quantum computing, end-to-end quantum encryption, secure software distribution, and entangled sensor arrays. In addition to entirely new algorithms and applications, networking protocols may need refinement or large-scale revision to work on nascent quantum network testbeds. A variety of network architectures may be envisioned, or encountered in the real world, and algorithms for distributed quantum computing will need to account for network topologies. Applications of sensor networks, including long baseline telescopes, Heisenberg-limited interferometry, and improved clock synchronization align both here and with frontiers 1, 2, and 5.

> ***"Quantum networking resources such as entanglement and teleportation are still not well understood among domain scientists who could exploit them to solve new classes of scientific problems."***
>
> *– Quantum Networks for Open Science Workshop (DOE/ASCR 2019)*

A key opportunity on this frontier is for researchers to develop and validate a sufficiently complete set of foundational quantum networking components that work together so long-distance quantum networks can then be designed, established and operated to distribute entanglement to multiple nodes on (and around) Earth. During the same period, novel algorithms could enable exploration of new applications for quantum networks. Several concepts such as blind quantum computing and quantum-enhanced telescopes could be tested and improved with empirical studies using quantum network testbeds or prototypes. Feasibility studies for space-based missions to distribute entanglement will combine concepts from quantum engineering (and technology readiness levels) with fundamental studies of entanglement generation, distribution, and utilization. Furthermore, new concepts for sensor arrays and distributed quantum computers are likely to be discovered as proofs-of-principle unfold.

7. Characterizing and Mitigating Quantum Errors

> ***"The grand challenge…for the Nation is understanding and experimentally realizing quantum error correction and, ultimately, fault tolerance at large scales."***
>
> *– RFI response*

Quantum systems are inherently sensitive to their environment, which inevitably leads to errors. This is a fundamental issue because controlled interactions make qubits useful, yet untamed interactions cause decoherence. The frontier of preserving coherent superpositions and entangled states long enough to perform valid quantum computations therefore relies on understanding how to diagnose, avoid, and mitigate quantum errors. Fighting such decoherence is essential for quantum metrology and networking, too. In addition to materials science and topological protection discussed in Section 3, improved control will be needed with explorations ranging from quantum error correction to decoherence-free subspaces and new approaches for fault-tolerant quantum computing. Key themes include: optimal characterization and control for multi-qubit systems, including use of measurement, feedback, and novel encodings; development and exploration of novel universal computing approaches in the fault-tolerant domain; and use of current devices to expand the limits of performance for qubits.

> ***"A variety of techniques have been used to characterize qubits and the operations (gates) performed on them. Currently, the two dominant techniques are randomized benchmarking (RB), and gate set tomography (GST)….Future protocols that directly probe the effect of changing how we implement gates will be critical for improving our devices and stabilizing them against drift."***
>
> *– ASCR Report on a Quantum Computing Testbed for Science (DOE 2017)*

a. Characterizing and Controlling Multi-qubit Systems

Exploring how, and to what extent, characterizations of 2-qubit gates enable predictions of system performance may be key for designing and controlling quantum computers at scale. New techniques may be needed to fully predict how errors propagate in complex quantum processors and networks. Characterization and modeling can guide the development of optimal gate operations, help mitigate coherent errors and crosstalk, and stabilize devices against drift. Quantum error mitigation opportunities named by members of the R&D community include improved materials (Section 3), multi-qubit measurements and feedback, improved control techniques and platform designs, and extensions to the fundamental theory of quantum error correction with novel encodings and protocols that may improve the threshold for fault-tolerance, and reduce overhead costs in terms of resources (qubits, gates, and times) for implementing logical qubits.

> ***"Uncovering new types of error correction and mitigation suitable for near-term simulators is an open problem. Furthermore, there is a natural trade-off between the coherence of a system and the degree of programmability and tunability. Understanding and exploring this trade-off is important in developing quantum simulators. There is also an opportunity in the development of algorithms with this trade-off in mind, leading naturally to the concept of co-design, i.e., developing applications for specific hardware and architectures. Such efforts will benefit from the convergence of various areas of expertise, including experimental physics, quantum control theory, computer science and software, and engineering."***
>
> *–Quantum Simulators: Architectures and Opportunities 2019*

b. Approaching the Fault-tolerant Domain

Quantum error mitigation will enable explorations of universal computing with systems approaching the fault-tolerant regime. Experiments in this direction can stimulate co-design efforts, for example with error-aware implementations of algorithms supported in ways that minimize use of particular gates, operations, or states that are prone to decoherence (as mentioned in Sections 2 and 4). Several R&D community inputs pointed out that developing a full stack—from physical to logical qubits and compilers with software to implement higher-level quantum circuits—opens a series of new directions for research. Explorations include new performance benchmarks (e.g., quantum volume or test-piece calculations) where results depend on error mitigation. Verification and validation will take on new urgency as fault-tolerant modules and co-processors become available. Error-correcting quantum repeaters and fault-tolerant approaches for adiabatic quantum computing and analog quantum simulation are related research challenges.

> ***"Research on quantum error correction can benefit enormously from using the current and near-term quantum computer hardware (often referred to as Noisy Intermediate Scale Quantum [NISQ] computers), which will allow error correction codes and protocols to be developed from in situ studies on real hardware rather than using idealized theoretical models."*** *– RFI response*

c. Using Current Devices to Expand the Limits of Qubit Performance

At the same time, even as error-corrected systems are in development, several voices have been clear that there is much to be learned from exploring newly available, albeit imperfect, technologies. Problems can be mapped to device-specific architectures to seek value in the near-term (as mentioned in Section 4). Explorations identified in this direction include examining what amount of error mitigation is required to realize useful computations, development of useful low-depth algorithms (e.g., approximate optimization), and finding practical strategies for tailoring quantum error mitigation techniques to specific hardware for specific applications.

"Quantum states are fragile; a great challenge is developing devices and techniques to reduce noise in quantum devices. All avenues should be explored, including topological materials and/or device designs that promise to reduce quantum state fragility, new error mitigation techniques, and quantum error correction codes."

– RFI response

In pursuit of fault-tolerance, both evolutionary and revolutionary pathways are being explored. Experiments with state-of-the-art qubits can push the envelope of performance, even with incremental developments. Improvements in support technologies such as lasers, microwave electronics, cryogenics, and foundries can provide valuable steps in this direction. Work at testbeds can hone quantum control methods (e.g., dynamical decoupling, pulse sequencing, and error correction), by facilitating learning through experimentation to develop and apply device-specific models of noise, control, and errors. Some of the more revolutionary approaches that were named include topological qubits (touched upon in Section 3), use of cluster states and symmetry-protected states as a resources for measurement-assisted quantum computing, studies of higher dimensional qubits such as oscillator encodings, and other novel qubit architectures.

"Quantum computers are intrinsically far more vulnerable to error than classical computers. Thus our hopes that large-scale quantum computers will be built and operated someday are founded on the theory of quantum fault tolerance, which establishes that reliable quantum computation is possible when the noise afflicting the computer has suitable properties. Recent insights are broadening the class of noise models for which fault-tolerant quantum computing is provably effective, and clarifying the overhead cost of overcoming noise."

– Report of the Workshop on Quantum Information Science (NSF 2009)

The vision for this frontier is to develop reliable logical qubits and other techniques for achieving fault tolerance. Development of more sophisticated error-corrected systems will benefit from improved methods for characterizing system performance and error propagation. Error corrected networks and processors would serve as a next generation of hardware to support testing and stimulate development of new algorithms and protocols for verification and validation. While both incremental and revolutionary approaches to enable large-scale fault-tolerant systems will continue to be explored, near-term applications for smaller-scale fault tolerant machines could be tested with a variety of architectures and contexts. Aside from its practical importance for quantum technologies, theoretical work on quantum error correction may stimulate further discoveries about fundamental mathematical and physical foundations of the universe, as discussed more in Section 8.

8. Understanding the Universe through Quantum Information

"This 'entanglement frontier' is exciting because, knowing that highly entangled systems of many particles are hard to simulate with digital computers, we may anticipate that surprising, illuminating, and useful new phenomena will occur in sufficiently complex quantum systems."

– Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing (DOE Study Group Report 2014)

QIS is a marvelous source of new perspectives on the mathematical and physical foundations of the universe. It has begun to transform the way we think about computation by exploring the limits of what can be computed with physical systems, and could provide new opportunities for testing quantum mechanics and other fundamental scientific theories in new regimes. Quantum technologies also provide new ways to search for physics beyond the standard model of particles and fields, often via precision measurements. In this frontier, foundational QIS research opens new scientific vistas. Three major themes underlie this frontier: exploring the mathematical foundations of computation and information through the lens of quantum computing and quantum information theory; using concepts from QIS and new applications of quantum simulation to explore the limits of physical theory, from dark matter to quantum gravity; and leveraging precision measurement and many-body quantum systems to test the expectations of the standard model of particle physics, and search for phenomena beyond the current model.

"Some important areas of research in entanglement theory aim to: deepen understanding of fundamental physical and mathematical aspect of quantum vs classical correlations (notably, 'monogamy' of entanglement, also in relation to the 'quantum marginal problem,' or relevant to temporal as opposed to spatial correlations); further push aspects of the characterization and quantification of entanglement within a resource-theory framework (with possible ramifications ranging from quantum thermodynamics to high-energy physics); ultimately, explore generalizations of the very notion of entanglement, that may incorporate 'locality constraints' more general than currently envisioned and may allow [researchers] to unveil the nature and role of entanglement in topological quantum matter or in the emergence of space-time geometry."

– Executive Summary of 2015 NSF Conference on Mathematical Sciences Challenges in Quantum Information (NSF 2015)

a. Exploring Mathematical Foundations of Computation and Information

Fundamental questions about computation (e.g., *Can quantum computers efficiently simulate any process that occurs in nature?* And, *for what computations might exponential speedup be achieved over classical approaches?*) raised in QIS workshops touch on quantum complexity theory, quantum resource theory, and quantum computing. Fundamental research on the cybersecurity implications of quantum technologies, and mitigation strategies, is a common area of interest for mathematics, computer science, and QIS experts. Open questions on the theoretical limits of error correction and topological quantum computing, and the universality of adiabatic quantum computation are also discussed in the RFI responses and workshop reports.

"Although several theoretical models of quantum computation exist and are well-studied, such as quantum circuits, topological quantum computation, dissipative quantum computing, quantum walks, and the adiabatic quantum computing model, each model has its pros and cons in the context of an actual hardware implementation. The space of possible quantum computational models is far from fully charted, and developing models in a co-design approach with quantum hardware development may benefit both."

– 2015 DOE ASCR Workshop

Investigating how complex quantum states can be prepared or efficiently approximated could inform the development of performance benchmarks, and also elucidate the origins of thermodynamics and non-equilibrium dynamics (e.g., via studies of time crystals, chaos, pre-thermalization, and quantum information scrambling). At the same time, advances in QIS are spurring improvements in classical computation—for example, with simulated quantum annealing or new approaches to Boson sampling that raise expectations for demonstrable quantum advantages. One workshop report suggested QIS can help answer the question, "Are there other fundamentally different models of computing that have not yet been developed?"

b. Expanding the Limits of Physical Theory

"[T]he field should think carefully about which key, longstanding questions in physics could be solved using quantum technology." *– RFI response*

Research in QIS has begun to shed light on other interwoven areas of physics and other scientific fields. For example, research on entanglement can address fundamental questions about the emergence of spacetime, entropy of black holes, correspondence with wormholes, and the foundations of thermodynamics. Research areas described in workshop reports and RFI responses include: how quantum computational analysis of quantum walks can extend scattering theory; how quantum error correction codes and multipartite entanglement can inform searches for new phases of matter and topological states; and how the anti-de Sitter/conformal field theory (AdS/CFT) correspondence and associated dictionary for translating results can be used to inform quantum gravity theory, and explore properties of gauge theories at strong coupling where perturbative analysis is not possible. Furthermore, quantum networks and computers can test quantum mechanics in new regimes by exploring fundamental limits for coherence and entanglement. QIS can help explore the question, "What credible deviations from conventional quantum theory are experimentally testable?" (e.g., gravitationally induced decoherence, spontaneous wavefunction collapse models, or nonlinear corrections to the Schroedinger equation).

"Focus on simulating quantum systems that cannot be studied in a lab, such as black holes." *– RFI response*

c. Testing the Standard Model of Particle Physics

For fundamental physics, in addition to improvements in gravitational wave detection and precision measurements of fundamental constants, QIS can provide new approaches to testing expectations from the standard model of particle physics, and conjectured extensions to that field. Examples include: searches for dark matter and dark energy; tests of fundamental symmetries such as charge, parity, time (CPT) and Lorentz invariance; and searches for variation of fundamental constants in time or space. QIS methods such as coherent spectroscopy, atom interferometry, or advanced magnetometry enable searches for permanent electric dipole moments of fundamental particles (tests of CP-violating physics), measurements of the fine structure constant (useful for tests of quantum electrodynamics), searches for axion-like particles (dark matter candidates), and fifth-force searches. This frontier will improve our understanding of the foundations of the physical universe.

"Ultra-precise measurements of quantum phenomena can be used as extremely powerful probes of new physics at very high energy scales, e.g., by testing fundamental physical symmetries and laws, and by searching for new phenomena such as that associated with the 'dark sector.' For example, one of the most exciting opportunities at the Quantum Frontier is searches for an electric dipole moment (EDM) of the electron, as well as related quantities in atomic nuclei, which arise at a measurable level only from charge-parity (CP) violation beyond that in the Standard Model." *– DOE Quantum Sensors Report*

This frontier recognizes the value of QIS R&D for deepening foundational knowledge, with the potential to yield unexpected discoveries, new scientific concepts and tools that translate to other disciplines, and yet unknown applications and technologies downstream. QIS research provides opportunities to test, refine and extend fundamental mathematical and physical theories that we use to describe the nature of the universe; develop a more complete understanding of what can and cannot be efficiently computed; and elucidate the value of quantum resources for computing, engineering and science itself.

SUMMARY AND OUTLOOK

Within these frontiers, what are the most pressing grand challenges facing QIS? The answer to that depends on one's objectives. The breadth of responses and details of R&D pursuits encouraged in the RFI responses and QIS workshop reports provide a broad range of opportunities for research agencies to consider and pursue according to their missions. This community input, received in multiple venues from U.S. and worldwide technical experts, has been organized into eight technical areas identified here as quantum frontiers. The frontiers are broad areas at the forefront of QIS that contain numerous quantum questions that should be explored early on, and hard technical challenges that must be overcome before applications can be developed.

Ensuring sustained American leadership in QIS hinges on coordinating core research programs across the pillars of QIS U.S. Government funding: the civilian, intelligence, and defense agencies. For each mission, the grand challenges and priorities may be different, but there are common hurdles where coordinated efforts can accelerate progress. The synopsis of R&D community perspectives presented here is intended to gently guide this coordination by pointing towards quantum frontiers to explore.

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

ABOUT THE NATIONAL QUANTUM INITIATIVE

The National Quantum Initiative (NQI) provides an overarching framework to strengthen and coordinate QIS R&D activities across U.S. Departments and Agencies, private sector industry, and the academic community. The NQI entails a whole of government effort to accelerate quantum research and development, as legislated by the NQI Act of 2018. The NQI Act authorizes the National Science Foundation (NSF), the Department of Energy (DOE), and the National Institute of Standards and Technology (NIST) to strengthen QIS Programs, fund Centers, and support Consortia. The NQI Act also calls for a coordinated approach to QIS R&D efforts across the Federal Government, including the civilian, defense, and intelligence sectors. NQI activities are coordinated through the NSTC Subcommittee on Quantum Information Science (SCQIS), with support from the National Quantum Coordination Office (NQCO).

ABOUT THE NATIONAL QUANTUM COORDINATION OFFICE

The National Quantum Coordination Office (NQCO) coordinates QIS activities across the U.S. federal government, industry, and academia. Legislated by the NQI Act of 2018 and established within the White House Office of Science and Technology Policy, the NQCO oversees interagency coordination of the NQI Program and QIS activities; serves as the point of contact on Federal civilian QIS activities; ensures coordination among the consortia and various quantum centers; conducts public outreach, including the dissemination of findings and recommendations of the NSTC Subcommittee on Quantum Information Science and the NQI Advisory Committee; promotes access to and early application of the technologies, innovations, and expertise derived from U.S. QIS activities, as well as access to quantum systems developed by industry, universities, and Federal laboratories to the general user community.

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A STRATEGIC VISION FOR AMERICA'S QUANTUM NETWORKS

Product of

THE WHITE HOUSE

NATIONAL QUANTUM COORDINATION OFFICE

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INTRODUCTION

The Trump Administration is committed to American leadership in quantum information science (QIS), and to unleashing its incredible potential for U.S. economic growth, technological advancement, and national security. To coordinate a national research effort encompassing Federal agencies, the academic community, and industry leaders already underway, The White House National Quantum Coordination Office has released *A Strategic Vision for America's Quantum Networks*.

Exploring how to build the quantum internet—a vast network of quantum computers and other quantum devices—will catalyze new technologies that accelerate today's internet, improve the security of our communications, and allow dramatic advances in computing. By leading the way in quantum networking, America is poised to revolutionize national and financial security, patient privacy, drug discovery, and the design and manufacturing of new materials, while increasing our scientific understanding of the universe.

Quantum computing and networking technologies are still at an early stage of research and development (R&D). The strategic vision focuses America's R&D efforts to advance the development of foundations for the quantum internet. It establishes QIS community goals for quantum networking, and recommends six specific technical areas for focused research activity.

This strategic vision is driven by the National Quantum Initiative Act (NQIA), signed into law by President Trump in December 2018, to accelerate QIS R&D through increased federal investment and coordination. The strategy was developed through the NQIA's coordinating bodies, the National Quantum Coordination Office (NQCO) and the National Science and Technology Council's Subcommittee on Quantum Information Science (SCQIS) and reflects deep community input from SCQIS request for information responses of 2018-2019 and from recent workshops hosted by Federal agencies[1,2].

Over the past year, as called for by the NQIA, The White House established the National Quantum Coordination Office to unify Federal R&D activities across government, and the National Quantum Initiative Advisory Committee to ensure perspectives from the quantum community inform Federal efforts. Additionally, to implement the NQIA, the National Science Foundation announced the Quantum Leap Challenge Institutes[3] solicitation to explore foundational quantum science and technology, and the Department of Energy (DOE) announced funding for the creation of new QIS research centers[4] where researchers from DOE's National Labs will join with experts from academia and the private sector to advance R&D. This builds upon the robust QIS research programs, centers and consortia at other agencies including National Institute for Standards and Technology, the Department of Defense, the National Security Agency, and NASA.

In 1969, the Department of Defense's Advanced Research Projects Agency demonstrated the first network (ARPANET) that led to the internet we know today. Back then, one could hardly imagine that it would become the world's most powerful driver for economic growth and quality of life.

As demonstrated once by ARPANET and now by *A Strategic Vision for America's Quantum Networks* and the NQIA, the Federal government has a critical role to play in driving early-stage QIS research and providing direction to national R&D efforts. Under the Trump Administration's leadership, the United States will pioneer the quantum internet and ensure QIS discovery and innovation that benefits all Americans.

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BUILDING THE FOUNDATIONS FOR NETWORKING QUANTUM DEVICES

Quantum networking uses the quantum properties of light and information to enable secure communication, new sensing modalities, and enhanced quantum computation. Research in this area will ensure continued advances in fundamental science and enable innovative applications of quantum devices to improve the Nation's economy and security. Long-term prospects for quantum networks hinge on our ability to pioneer platforms that reliably link together quantum devices, and to develop applications that leverage quantum-enabled security, sensing, and computation modalities. By making a concerted and sustained effort to develop these prospects, the foundations for a quantum internet will be in place to enhance America's future.

Two specific goals will focus efforts in this direction:

- Over the next five years, companies and laboratories in the United States will demonstrate the foundational science and key technologies to enable quantum networks, from quantum interconnects, quantum repeaters, and quantum memories to high-throughput quantum channels and exploration of space-based entanglement distribution across intercontinental distances. At the same time, the potential impact and improved applications of such systems will be identified for commercial, scientific, health and national security benefits.
- Over the next twenty years, quantum internet links will leverage networked quantum devices to enable new capabilities not possible with classical technology, while advancing our understanding of the role entanglement plays.

While pursuing these goals, key opportunities for new directions and spin-off applications will be encouraged by strong coordination and future-looking leadership under the auspices of the National Quantum Initiative's coordination mechanisms. This includes both the strong support of federal agencies performing the research and development and also a dedication to using the new technologies and scientific discoveries to enhance the execution of agency missions.

Accordingly, the National Science and Technology Council Subcommittee on Quantum Information Science recommends pursuing the following activities, commensurate with our growing understanding of their relevance to useful quantum networking and other quantum technology:

- Technology and platform development for key components including classical sources, quantum-limited detectors, ultra-low loss interconnects, space-to-ground connections, and classical networking and cybersecurity protocols and scaling costs;
- Transduction of quantum sources and signals from optical and telecom regimes to quantum computer-relevant domains, including microwaves;
- Entanglement and hyper-entangled state generation, and transmission, control, and measurement of quantum states;
- Development of quantum memories and small-scale quantum computers that are compatible with photon-based quantum bits in the optical or telecom wavelengths;
- Exploration of novel algorithms and applications for long-range entanglement between small-scale and large-scale quantum processors, including quantum error correction, quantum cloud computing protocols, and new quantum sensing modalities; and
- Exploration of techniques for both terrestrial and space-based entanglement distribution.

ABOUT THE WHITE HOUSE NATIONAL QUANTUM COORDINATION OFFICE

Established by the National Quantum Initiative Act of 2018 to reside within the White House Office of Science and Technology Policy, the National Quantum Coordination Office coordinates quantum information science research and development across the Federal Government. Providing a central point of contact for stakeholders working in the field, the NQCO supports the various interagency groups and coordination mechanisms to ensure a cohesive and sustained approach for American leadership in quantum information science.

ABOUT THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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

ABOUT THE NSTC SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

The NSTC Subcommittee on Quantum Information Science (SCQIS) coordinates Federal research and development (R&D) in quantum information science and related technologies under the auspices of the NSTC's Committee on Science. This coordinated R&D aims to ensure that U.S. leadership in quantum information science and its applications is maintained and expanded over the next decade. The SCQIS is co-chaired by the Department of Energy, the National Institute of Standards and Technology, the National Science Foundation, and the White House Office of Science and Technology Policy. Additional members include the Department of Defense, National Aeronautics and Space Administration, National Security Agency, Office of the Director of National Intelligence, Office of Management and Budget, United States Patent and Trademark Office, and the Department of State.