POLICY FORUM

QUANTUM INFORMATION

The U.S. National Quantum Initiative: From Act to action

Academia, agencies, and industry will work together

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Although quantum information science and technology (QIST) is based on fundamental physical tenets familiar to many in the academic world, it remains alien to much of the industrial and engineering workforce that will actually build reliable quantum devices. Industrial investment in QIST has grown considerably in recent years, but the field is at an embryonic stage, and formidable technical challenges to building quantum technologies remain. This confluence of opportunity, need, and challenge suggests that governments will have a substantial role in developing QIST and its ecosystem and in translating the corresponding science and technology for the benefit of society. We outline one such initiative, the U.S. National Quantum Initiative (NQI), and discuss how it can play a vital role in advancing QIST.

Conventional information technology is based on bits—the basic unit of information—which take on one of two possible values: 0 or 1. At the microscopic level, quantum physics allows information to be represented and processed in a very different manner. Elementary objects such as photons or electrons can be placed into quantum superposition states, which contain the possibility of emerging in either of two states upon observation.

Early U.S. investment in the development of QIST began even before Peter Shor discovered his eponymous quantum algorithm for factoring large numbers, central to cryptography. The U.S. intelligence community and Department of Defense have made substantial investments in quantum information science at academic and government laboratories in the United States and abroad. The National Institute of Standards and Technology (NIST) began an effort in its laboratories in the 1980s that has continued to grow, and the National Science Foundation (NSF) has a three-decade record of supporting a diverse complement of QIST researchers. More recently, the U.S. Department of Energy (DOE) Office of Science and laboratories have helped expand team-based efforts, and agencies such as NASA continue smaller-scale research and development.

Now, the National Quantum Initiative Act, which passed with strong bipartisan support in Congress and was signed into law by President Trump in late 2018, instructs the NIST, NSF, and DOE to work with academic institutions and private industry to catalyze the growth of QIST, largely through formation of the NQI. The NQI looks to follow a science-first approach that will stimulate development and use of new technologies spanning academia, government laboratories, and industry. This approach will enable collaboration across borders, as other countries embark upon similar paths.

FROM BITS TO QUBITS

Quantum information science aims to develop new forms of information processing systems, spanning three broad categories: sensing, computing (including simulation), and networking (*1*). Underlying theory provides basic-science insights into nature—for example, in understanding complex interacting systems and black holes. More practically, the advent and impact of atomic clocks, advanced laser interferometers, and nuclear magnetic resonance indicate that continuing development of quantum technology may usher great scientific opportunities in many other areas. Just as the LIGO gravitational wave detector enables scientists to peer into the cosmos with new eyes, quantum technology opens windows into a realm governed by the laws of quantum physics. And quantum computers will advance fundamental science by providing computing power to simulate a host of currently intractable problems.

Sensing

A long-standing goal of QIST is to develop sensors that are enhanced by employing quantum physics. Some devices, such as atomic clocks or laser rangefinders, use well-known aspects of quantum physics to provide uncanny accuracy. Others engage in more esoteric domains, such as quantum entanglement, to yield orders-of-magnitude improvements in performance or sensing in new regimes, such as inside living cells.

The next generation of quantum-based sensors is projected to outperform current technologies in several areas (*2*). Atomic interferometer-based gravity sensors and accelerometers are applicable to geo-exploration and Global Positioning System (GPS)–free navigation; nanoscale diamond magnetic-field sensors can be used in biological and medical research, such as nanoscale functional imaging of individual molecules and in biomedical diagnostic technology; and quantum techniques can enhance the sensitivity and robustness of optical measurements.

Computing

A longer-term goal is the construction of quantum computers, which will use elementary quantum objects to represent and process quantum bits—qubits. Instead of storing each bit of information (as 0 or 1) in each hardware component made of millions of atoms (making it governed by classical physics), a quantum computer stores information in a way that is governed by quantum physics (e.g., storing each bit in a separate, single atom). Quantum modes of behavior, including superposition and entanglement, make the computer operate in different ways than classical digital computers.

Although many calculations would remain daunting for a quantum computer, there are key applications where quantum computers dramatically outperform classical computers. A fully functioning quantum computer would radically enhance our capabilities in simulating nuclear and high-energy physics; designing new chemicals, materials, and drugs; breaking common cryptographic codes; and performing more speculative tasks such as modeling, machine learning, pattern recognition, and optimizing hard logistical problems such as controlling the electric energy grid or traffic control systems (*3*).

The race is on to go beyond the current status of small numbers of high-quality qubits or large numbers of low-quality qubits, to construct the first generation of universally programmable quantum computers. The

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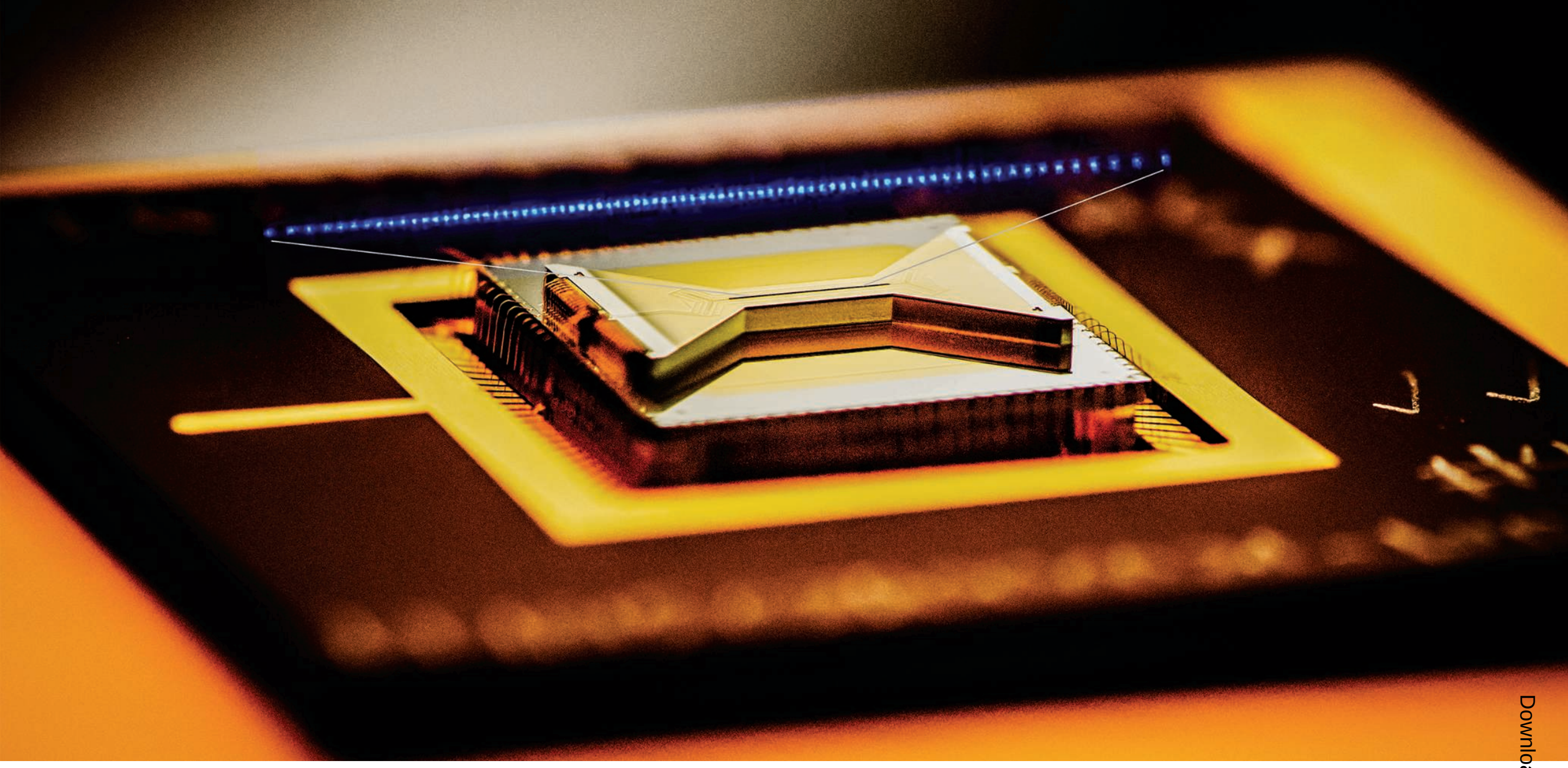

A semiconductor chip ion trap, fabricated by Sandia National Laboratories, is composed of gold-plated electrodes that suspend individual atomic ion qubits above the surface of the chip. The chip (bow-tie shape) is about 10 mm across. The inset is a magnified image of 80 atomic $^{171}Yb^{+}$ ions glowing from scattered laser radiation.

coming years will see quantum computers with over 100 high-quality qubits, and the first computations for which no conventional computer can provide answers (*4*). On the far horizon remains the prospect of fault-tolerant, scalable devices that may fully realize the potential of quantum computing.

Communication Networks

A third major goal in QIST is to develop a global communication system capable of sending qubits between distant locations. Using qubits instead of conventional bits makes it possible to create shared randomness between parties while knowing whether the communication channel has been compromised by an eavesdropper. This enables sending information securely.

Quantum communication can also allow secure communication between multiple parties, and for interconnecting large-scale quantum computers via a "quantum internet" (*5*, *6*). A promising near-term application would be the deployment of a global network of linked high-precision atomic clocks for improving the timing precision across the network (*7*). This is needed, for example, for a more accurate GPS and other location-sensitive applications.

Although these three thrusts may seem disparate, they will progress and grow together. Building a large quantum computer will almost certainly require modular networks of smaller quantum computers linked by quantum communication networks analogous to the architecture of multicore conventional processors (*8*). Performing quantum communication over long distances will likely require small quantum computers as "repeater" stations installed between the nodes. Advanced quantum sensors, such as improved single-photon or single-spin detectors, will find use in quantum computing and communication.

BUILDING QUANTUM TECHNOLOGY

There are a host of physical platforms available for quantum technology, and they are very different from the devices used in conventional information processing. Quantum systems must be extremely isolated from the environment to preserve their superpositions and entanglement of qubits in a quantum memory. This requires exotic features such as cryogenic temperatures, superconducting circuitry, atomic-level perfection of solid-state crystals, ultrahigh-vacuum environments, or laser control of electromagnetically confined individual atoms. Transmission of quantum information between memory locations will likely require the use of quantum electromagnetic fields (photons), which propagate through air or in optical fibers with little degradation.

Scaling up from established single-qubit behavior to a many-qubit operation will likely require a combination of the above-mentioned technologies. Large-scale quantum computers or communication networks may be tied together using optical fibers, photonic switches, and network technology. Integrating many forms of quantum technology, including hardware and software, is central to developing quantum information technology.

Bringing quantum technology to fruition will require both bottom-up and top-down approaches to integrating the pieces of a quantum information network or computer (*9*). Experts in individual quantum platforms, such as superconducting circuits, individual spins in a semiconductor, or trapped atomic ions, will have to engineer their systems to be so reliable that nonexperts and software designers can use the systems to create future applications.

Risks

A well-known example of a quantum technology is a computer that could break the security of many of our current data-encryption methods, which are based on the difficulty of finding the factors of very large numbers. Shor's quantum factoring algorithm offers an exponential speedup in cryptanalysis compared to any known classical algorithm. This poses the risk that the internet as we know it, which is made secure under the secure hypertext transfer protocol, might cease to function as it does now. Although mathematicians are developing new encryption methods that are not known to be breakable by a quantum computer, and government agencies such as NIST are working with industry to implement and deploy them, it has not been proven that any purely mathematics-based method is unbreakable.

Another risk associated with a large, expensive effort is failure from the unexpected. Although the scientific consensus is clear that no fundamental, physics-based barriers exist to creating quantum technologies, the technical challenges to doing so may be far more daunting than is currently believed. Qubits are notoriously susceptible to perturbation

PHOTO: KAI HUDEK/UMD/IONQ AND E. EDWARDS/JQI by the tiniest of "errors" in operation or to any unwanted influences, such as electrical noise that is present in any computer system. Theorists have proven that such errors can be managed and corrected, as long as the rate of errors is low enough and their nature is well understood. Still, there might be unexpected kinds of errors or failure modes. Studying such noise and errors will constitute a large part of the research and development effort.

Other potential risks fall into the broad category of yet-to-be-discovered. Quantum technology might create unanticipated risks to privacy and to social manipulation, not unlike conventional information technology and artificial intelligence. Legal and ethical questions cannot be ignored as the capabilities become clearer.

ACADEMIC AND INDUSTRIAL APPROACH

University scientists are adept at discovering new principles in basic or applied science. Industry excels in converting such principles into well-engineered products. In mature subjects, such as classical optical engineering, there is a well-developed continuum connecting scientific discovery with product development, where technology transfer activities are routine. This continuum is not present for QIST. Universities do not have easy, affordable access to the most advanced design and fabrication capabilities, and industry rarely has the deep physics expertise needed for translating quantum science into products.

The need, then, is to create a bridge between basic scientists and engineers to learn how to translate quantum science into quantum technology. This can be best accomplished in the short term by building focused teams that include both groups working together on common, well-defined goals. Attention will need to be paid to complicating factors such as intellectual property and the different reward cultures of universities and industry.

In the longer term, we must develop a quantum-smart workforce. Universities can train a larger number of quantum-capable engineers and basic scientists who wish to work alongside engineering professionals. The challenge is in developing students' interest in QIST early in their academic career while quickly ramping up new curricula at universities in a way that serves the real needs of industry.

Both hardware and software facets of QIST are in need of a larger workforce. On the software side, many university departments of computer science have only just begun hiring faculty specializing in QIST algorithms. Industry could encourage such hiring by providing grants or gifts to departments interested in doing so, and the government can use existing mechanisms to encourage new curricular and faculty development. Universities can recognize QIST as a growing aspect of computer science, and create new faculty positions in this area.

GOING FORWARD

The NQI will support scientific research with new programs at the individual investigator level and large, center-scale efforts, alongside a comprehensive approach to workforce development and industrial engagement. This breadth highlights the need for a whole-of-government approach to QIST. Many agencies already play key roles, with different goals and missions driving different aspects of research. Although the NQI is to be led by NIST, NSF, and DOE, coordination of these efforts with complementary approaches from the defense and intelligence communities can improve how research funds are spent and infrastructure is used.

The White House Office of Science and Technology Policy has convened the National Science and Technology Council's Subcommittee on Quantum Information Science (SCQIS), which enables interagency coordination beyond the implementing agencies and which highlighted opportunities for the National Quantum Initiative Act (*10*). The new National Quantum Coordination Office announced in March will provide a centralized means of connecting stakeholders.

> ***"Attention will need to be paid to...the different reward cultures of universities and industry."***

The NQI can enable improved engagement of the private sector with academia and government. Industrial consortia such as the Quantum Economic Development Consortium that NIST is developing, combined with innovation-driven research and development made possible by both small-scale and larger, center-style efforts, are one aspect of this approach. Enabling entrepreneurs and encouraging appropriate investment by working with capital markets and providing timely, useful information are another.

These coordination and industrial engagement aspects combine with improved use of shared facilities and new infrastructure. Modeled in part on other scientific domains such as particle physics and astronomy where research needs outpace individual or group-level capabilities, the NQI-related infrastructure will help push the edge of technology and research.

Much discretion will remain at the agencies to ensure a science-first approach to research. The NSF has announced a variety of new opportunities, such as the Quantum Leap Challenge Institutes, and the DOE is working with stakeholders to develop large-scale efforts to expand their burgeoning QIST portfolio. This rapid growth of programs turns the challenge back to the research community to drive forward the basic science. At the same time, building connections between governmental, academic, and industrial stakeholders—ranging from front-line researchers to teams building functioning quantum devices to end-user businesses and individuals—will help realize the opportunities QIST can provide. Maintaining open discussion in this community will help mitigate many challenges, from growing workforce needs to better economic forecasting to solving scientific problems. These conversations, in turn, can reduce fragmentation of research efforts, improve investor decision-making and risk evaluation, and promote the innovation cycle of research driving products, which in turn drives revenue, leading to more research investment.

The NQI can also enable improved international cooperation, with agencies developing or expanding partnerships with international efforts in areas such as open standards for QIST and foundational research. For example, major QIST initiatives are being undertaken by the European Union, the United Kingdom, Japan, Canada, Australia, and China (*11*). Such QIS initiatives and investments by international partners provide invaluable resources to QIS research. Facilitating international cooperation with like-minded stakeholders, ranging from education to development, will ensure a healthy scientific ecosystem going forward. ■

REFERENCES AND NOTES

1. J. Stajic, *Science* **339**, 1163 (2013).
2. C. L. Degen, F. Reinhard, P. Cappellaro, *Rev. Mod. Phys.* **89**, 035002 (2017).
3. J. Preskill, *Quantum* **2**, 79 (2018).
4. National Academies of Sciences, Engineering, and Medicine, *Quantum Computing: Progress and Prospects* (National Academies Press, 2018); https://doi.org/10.17226/25196.
5. H. J. Kimble, *Nature* **453**, 1023 (2008).
6. S. Wehner, D. Elkouss, R. Hanson, *Science* **362**, eaam9288 (2018).
7. P. Kómár *et al.*, *Nat. Phys.* **10**, 582 (2014).
8. M. G. Raymer, K. Srinivasan, *Phys. Today* **65**, 32 (2012).
9. C. R. Monroe, R. J. Schoelkopf, M. D. Lukin, *Sci. Am.* **314**, 50 (2016).
10. National Science and Technology Council, National Strategic Overview for Quantum Information Science, September 2018; www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf.
11. *Quantum Sci. Technol.* **4** (April 2019).

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