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Perspective
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Promoting Strong International Collaboration in Quantum Technology Research and Development

Quantum technology holds the promise of producing new computers, sensors, and communication systems that can gather, transmit, and process information in ways that far surpass our current capabilities, with potentially dramatic benefits to economic prosperity and national security. It also poses potential risks to national security and economic stability: One of the best-known applications of future quantum computers is the ability to rapidly break the encryption systems used to protect today's internet traffic, potentially exposing sensitive information, such as health records, commercial transactions, and defense-related communications, to hostile interception. In September 2022, National Security Advisor Jake Sullivan specifically identified quantum technology as one of "a select few technologies [that] are set to play an outsized importance over the coming decade."[1] Most quantum technologies are still at an early stage, but given the strategic importance that they are likely to play in the coming decades, the Trump and Biden administrations and the past several Congresses have all moved aggressively to promote their development.

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The U.S. government has also identified the task of strengthening partnerships with allied and partner nations as a national priority, particularly in the context of national security.[2] An important part of this effort includes strengthening technology cooperation, especially the development of potentially transformative emerging technologies.[3] For example, the "Quad" dialogue between Australia, India, Japan, and the United States has defense technology research and development (R&D) as an explicit goal,[4] and in June 2021 the United States and European Union formed a Trade and Technology Council to promote R&D cooperation.[5] But operationalizing international collaboration in technology R&D is easier said than done: Every technology brings with it a host of challenging and often technical policy questions, such as protecting domestic intellectual property (IP) and sensitive technical information, balancing domestic and foreign economic interests, and avoiding unintended consequences (such as prompting competitor nations to develop their own production capacity).

Quantum technology is no exception. In this Perspective, I will briefly consider some of the many challenges and policy options for promoting healthy collaboration with allied and partner nations in quantum R&D. The primary audience is policymakers throughout the U.S. government who might eventually be involved in international cooperation with these nations regarding quantum technology. These policymakers could work in many U.S. government agencies, such as the Departments of Commerce, Defense, Energy, Homeland Security, Justice, State, and Treasury; National Aeronautics and Space Administration (NASA); National Science Foundation; and White House Office of Science and Technology Policy. This Perspective may also be of interest to policymakers in allied and partner nations, public policy researchers, and academic scientists and quantum technology industry workers who may eventually be influenced by policies that the U.S. government could set in this area.

In this Perspective, I do not assume any prior technical background on the reader's part, and I do not focus on the technical details of quantum technology approaches or applications.[6] I do not make concrete recommendations; instead, my goals are to (1) discuss several of the most relevant questions facing policymakers in this area, (2) explore the relevant trade-offs, and (3) suggest (hopefully useful)

Abbreviations

AI	artificial intelligence
DARPA	Defense Advanced Research Projects Agency
IP	intellectual property
NATO	North Atlantic Treaty Organization
NIST	National Institute of Standards and Technology
NSA	National Security Agency
NSTC	National Science and Technology Council
PQC	post-quantum cryptography
PRC	People's Republic of China
QED-C	Quantum Economic Development Consortium
QIST	quantum information science and technology
QKD	quantum key distribution
R&D	research and development
UK	United Kingdom

frameworks for thinking about these policy questions. I begin by introducing the strategic context and current global landscape of quantum R&D, then discuss the motivations for international collaboration before going into five specific policy areas in more detail. I conclude by proposing a desired end state for the U.S. quantum technology ecosystem that policymakers may find useful for making policy decisions related to international collaboration.

Strategic Context of Quantum Technology R&D Cooperation

Since the end of the Cold War, the United States has been the world's leading superpower in advanced technology R&D, with the world's most-dynamic and most-inventive university and laboratory systems (for basic research) and private industries (for applied development and commercialization). But in recent years, that technology leadership has ceased to be as secure, as leadership in several advanced technologies (such as 5G, batteries, and advanced semiconductor fabrication) have arguably moved to other nations. One of the main causes of this shift is the rise of the People's Republic of China (PRC) as the "most consequential strategic competitor" of the United States.[7] Chinese President Xi Jinping has vowed to "win the battle" with the United States over developing critical technologies.[8]

The United States has responded by placing a renewed emphasis on retaining (or regaining) leadership in advanced technology R&D. The highest-profile recent act of Congress on this front came in July 2022, when Congress passed the bipartisan Chips and Science Act, which invests $52 billion to promote U.S. semiconductor manufacturing.[9] This law followed the less well-known bipartisan National Quantum Initiative Act (passed in December 2018), which identified quantum technology as a strategic technology priority for the United States, authorized up to $1.2 billion in quantum technology R&D over a five-year period, and established the National Quantum Coordinating Office within the White House Office of Science and Technology Policy.[10]

The passage of these laws reflects a renewed willingness of the U.S. government to engage in *industrial policy*: targeted policies aimed at promoting or preserving key technology sectors that the government has determined to be strategic priorities for national security or economic welfare. After a period of relative unpopularity from the 1980s through the mid-2010s, there is now a renewed willingness to experiment with industrial policy on the part of major U.S. political parties,[11] allied nations,[12] international financial institutions,[13] and the Chinese government.[14] For better or worse, this expansion of the window of politically feasible economic policy opens up new options for promoting and protecting advanced technologies related to quantum, such as the broad new export controls that the U.S. Commerce Department created in October 2022 for semiconductor sales to China.[15]

The White House Office of Science and Technology Policy's National Science and Technology Council (NSTC)'s *National Strategic Overview on Quantum Information Science* reflects the administration's prioritization of strong ties with partner nations by identifying "advancing international cooperation" as one of six key policy opportunities related to quantum technology.[16] The U.S. government has also signed several joint statements and international agreements specifically promoting cooperation in quantum technology R&D,[17] including

- joint statements between the U.S. government and the governments of Japan, South Korea, the United Kingdom (UK), Australia, Finland, Sweden, Denmark, Switzerland, and France[18]
- a "focus on quantum technologies" announced by the leaders of the Quad dialogue of Australia, India, Japan, and the United States[19]
- the Australia–UK–United States (AUKUS) defense technology cooperation agreement, which includes an AUKUS Quantum Arrangement to accelerate "generation-after-next" quantum capabilities.[20]

These statements are broad and high-level, with few policy specifics. In the rest of this Perspective, I will explore what constructive international cooperation in quantum technology R&D might look like in more-concrete terms.

International Quantum Technology Landscape

Quantum technology is a complicated and technical subject, and a detailed technical explainer is beyond the scope of this Perspective. The references contain several much more detailed explanations of quantum technology and its potential applications.[21] Very briefly, proposed quantum technology applications are often divided into the following three categories:

1. *Quantum computing* refers to a new type of computer, operating on fundamentally different physical principles from all previous computers, that can use basic building blocks known as *qubits* to perform certain types of calculations exponentially faster than all other computers. The eventual applications are still highly uncertain, but proposed applications include the scientific simulation of physical systems (e.g., biochemistry or new materials), high-performance numerical optimization, and (more speculatively) artificial intelligence (AI). From a national security standpoint, the most important known application is the ability to quickly break the encryption used to protect internet traffic. The National Security Agency (NSA) has described the consequences of a bad actor gaining this capability as "devastating to . . . our nation" if no countermeasures are taken.[22]
2. *Quantum sensing* refers to various types of sensors that measure (for example) gravity, acceleration, magnetic fields, or electromagnetic radiation, as well as atomic clocks that measure time very precisely. Some proposed quantum sensors use the principles of quantum physics to approach the highest sensitivity known to be physically possible. Others offer greatly improved stability or reduced size, weight, or power in comparison with existing sensors.
3. *Quantum communications* refers to systems that transmit information over long distances in the form of quantum states, such as individual microscopic particles known as *photons*, rather than over the classical electromagnetic waves that are typically used. One proposed application is for *quantum key distribution* (QKD), a communication system that might enable a highly secure form of message encryption (which is not vulnerable to decryption by future quantum computers). Other proposed applications include networking together future quantum sensors or quantum computers.

The global quantum ecosystem is growing rapidly but is still nascent. No quantum technologies have yet clearly demonstrated any practical commercial applications, except for atomic clocks (which, for example, underpin the Global Positioning System [GPS]). Quantum technology remained a primarily academic research endeavor until around 2014–2017, when several large tech companies around the world established major quantum R&D programs and a large burst of quantum tech start-ups were founded. Since then, these start-ups have raised billions of dollars worldwide.[23] Companies are pursuing a large number of technical approaches in parallel, and there is no single industry technical leader. Although these companies are performing a very large amount of R&D into potential near-term applications, the timelines to useful applications remain unclear. In fact, many market analysts believe that the near-term economic value of quantum tech is overhyped and that the level of financial investment is unsustainable and is far outrunning the current state of the technology. If so, there could be a sudden collapse in private investment that leads to a *quantum winter*: a period of disillusionment and technical stagnation similar to the AI winters in the late 1970s, 1980s, and early 1990s.[24]

In a 2022 report, I and other RAND researchers found that global technology leadership in these areas is complex and dynamic.[25] In quantum computing, the United States is the overall world leader by a wide variety of metrics, but China gained significant ground in 2021, and U.S. leadership is no longer indisputable.[26]

Quantum sensing is the most difficult category to assess systematically because of the much smaller overall market, the wide diversity of applications and technical approaches,[27] and the relative lack of reporting in the open scientific literature. The United States appears to be a world leader in this area—particularly in regard to actual deployment outside the lab—but Europe is strong as well, while China lags significantly behind.[28]

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In quantum communications, China is the clear world leader, particularly in QKD, having deployed QKD networks over thousands of miles in eastern China and having launched the world's only quantum communications satellite.[29] Europe, Japan, and South Korea have announced plans for large-scale QKD networks as well. But it is unclear how useful QKD will be in practice; for example, the NSA does not support the use of QKD in national security systems, citing its high costs and lack of flexibility.[30] The U.S. government has provided somewhat ambivalent messaging regarding the utility of quantum communications overall, stating that "[o]nly a handful of anticipated use cases have been identified" and specifying that "QKD does not currently motivate the U.S. Government to build large quantum networks," while also (1) acknowledging that eventual applications are likely and (2) recently increasing funding for quantum networking research.[31]

The United States and China are the two leading nations in quantum technology by many metrics, but they are far from the only two major players. The global landscape is very complicated, with other nations leading in certain subtechnologies. Moreover, most quantum researchers in the United States are in academia, where more than half of graduate students in relevant fields (and two-thirds of postdoctoral researchers) are foreign nationals.[32] About half of U.S. quantum science publications have a coauthor from a foreign institution, and U.S. researchers coauthor more papers with China than with any other country. Moreover, the United States is dependent on European and Japanese firms for several critical components and materials for quantum devices. In short, the United States is not self-sufficient in either quantum technology research or production.[33]

Motivations and Models for International Collaboration in Technology R&D

Previous literature has examined the large-scale drivers of international research collaboration and divided them into a *narrow paradigm* and a *broad paradigm*.[34] The narrow paradigm focuses on directly improving a nation's quality and scope of scientific research. For example, drivers within the narrow paradigm might include a desire to leverage specific technical expertise or to access a unique resource, such as the Atacama Cosmology Telescope in Chile (which benefits from Chile's uniquely favorable geography for astronomy). The broad paradigm also includes wider policy goals—usually, goals that are simultaneously advanced by policies that are not specific to science and technology—such as fostering stable and trusting diplomatic relationships with allies and partners.[35] Even research cooperation with adversary nations can have strategic benefits beyond the science itself.[36]

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The distinction between these two paradigms is not completely sharp, because many scientific discoveries eventually contribute to broader strategic goals, such as economic or military competitiveness. Both paradigms are clearly in play within the U.S. government's perspective on quantum R&D collaboration. As noted above, technical talent and critical components are globally distributed, and the United States does not have the technical capacity to advance the state of the art alone. But the push for strengthening quantum science and technology cooperation is also part of a broader, governmentwide effort to strengthen ties with allies and partners.[37] It is probably not a coincidence that the State Department signed its joint statements of quantum science and technology cooperation with Finland and Sweden shortly before those countries formally agreed to apply for North Atlantic Treaty Organization (NATO) membership in response to Russia's February 2022 invasion of Ukraine.

Another useful axis for characterizing international science and technology activities is along a spectrum from organized (or *top-down*) to spontaneous (or *bottom-up*).[38] The quintessential top-down activity is governed by a formal arrangement between governments or large organizations, typically with an agreed-upon division of budget and labor, whereas the quintessential bottom-up activities are initiated organically by small groups of individual researchers.

Most of the best-known examples of international R&D collaboration are top-down "big-science" projects, such as the Human Genome Project, the International Space Station, and the Large Hadron Collider particle accelerator. Given the significant effort required to sign formal international agreements, these tend be expensive projects undertaken within the broad paradigm. For example, the 1993 initiation of the International Space Station was partly done to symbolize the improved ties between the United States and Russia after the end of the Cold War. But an even more important driver of top-down collaboration for large R&D projects is cost and labor savings. Most international big-science projects that the United States has undertaken have been scientifically *derisked*—i.e., it is reasonably clear that the project is technically challenging but achievable—but require more resources than any one nation is willing to commit. (The three projects mentioned above were estimated to cost $3 billion, €100 billion, and $5 billion, respectively, and collectively required tens of thousands of workers.[39])

Top-down R&D collaborations are often successful for projects for which scientific advancement is the main driver, even if other goals are being pursued as well. All three of the big-science projects mentioned above were widely successful on scientific grounds, regardless of whether they justified their high price tags. But such collaborations can be challenging when combined with direct national security concerns. A very different example of top-down international R&D collaboration was the combined U.S.-Japanese FS-X Fighter development program. The original U.S. policy goal was to discourage the Japanese from developing their own fighter and to maintain Japanese reliance on U.S.-manufactured materiel. But because of a series of conflicting internal incentives and poor coordination within the U.S. government, this goal failed, and the FS-X Fighter was developed almost entirely indigenously by the Japanese.[40] There have been very few examples of successful international R&D programs in the military sphere, given the many logistical and political challenges to such cooperation.[41]

Could these top-down big-science projects serve as a model for future quantum technology R&D projects? Probably not. That model works best for scientific areas that meet the following three criteria:

1. A single clear "deliverable"—either physical infrastructure, such as the International Space Station, or a dataset, such as the human genome sequence—could greatly advance the field.
2. This deliverable requires large resources but has a reasonably clear scientific path to success, even if some engineering processes still need to be refined.[42]
3. There are no direct national security sensitivities, which greatly complicate international collaboration.

No field of quantum technology clearly meets these three criteria today, at least for the United States. Quantum sensors will probably be (individually) small-scale and will not require high *marginal* costs of production. Moreover, their national-security applications could complicate international collaboration. For example, the U.S. government already imposes export controls on quantum sensors that could complicate R&D collaboration, although it does not impose export controls on any other quantum technology applications as of this writing.[43] A transnational quantum communications network would be a natural candidate for international R&D collaboration, and the European Union has declared an intention to deploy exactly such a network.[44] But given the U.S. government's official rejection of QKD, its general lack of confidence in the utility of large-scale quantum communications networks, and its lack of geographic neighbors that are actively pursuing such networks, the United States does not appear likely to pursue such a project for the foreseeable future, at least not at the federal level.

Quantum computing is unlikely to be a candidate for top-down international collaboration either. There is still high uncertainty regarding the best fundamental scientific approach (e.g., qubit type), so few organizations are likely to risk committing huge resources into a suboptimal approach. Moreover, when quantum computers become mature, well-funded organizations (whether federally funded or corporate) will *probably* have enough resources to build large-scale quantum computers on their own. But this is not completely guaranteed. A large-scale (or, more precisely, *fault-tolerant*) quantum computer capable of executing the most-powerful known quantum algorithms will require a capability known as *quantum error correction*, which is believed to require huge physical resources. For example, the ability to break modern encryption systems is estimated to require about 20 million qubits, while today's largest quantum computers only use about 100 qubits.[45] A striking diagram of Google's vision for a future large-scale quantum computer shows a device that will be about the size of a basketball court.[46] It is conceivable—although very unlikely—that scientific progress might eventually reach a point at which researchers in multiple countries can reliably manufacture error-corrected qubits, but only at great expense and labor, while the applications (and economic value) of a fault-tolerant quantum computer remain unclear. In the unlikely event that all these conditions hold, a cost-sharing collaboration like the one that built the Large Hadron Collider might become financially appealing.

But even in this case, political and logistical challenges to cooperation are likely to abound. A large-scale quantum computer will be capable of breaking encryption unless countermeasures have already been widely adopted, so such a computer would have serious national security implications on a level similar to an advanced weapon system. Government-led collaboration would therefore be very challenging, as discussed above. Such a collaboration could be attempted by large corporations instead; however, by the time the technology approaches the required level of maturity, corporations will likely have to deal with tight government regulations on the manufacture and export of technology that affects national security.

So, for the foreseeable future, any international collaboration in quantum technology R&D will almost certainly remain bottom-up, informal, organic, and decentralized.[47] Such bottom-up international quantum collaboration is already strong today. For example, about half of quantum scientific publications that have a U.S. author also include a non-U.S. author,[48] and the U.S. companies Google, Microsoft, and ColdQuanta each have quantum research centers in Australia alone. Nevertheless, the U.S. government will need to set policies that promote a healthy ecosystem that encourages the exchange of scientific ideas while protecting sensitive information and IP. Doing so will require facing trade-offs in several areas.

Five Policy Areas Concerning Healthy and Responsible Collaboration

U.S. policymakers will need to set policy along many dimensions that affect international R&D collaboration. In this section, I briefly discuss five of them: international flows of human talent and research funding, standard-setting, supply chains, export controls, and technology approach diversification.[49] A common theme is that potential policies for all five dimensions lie along a spectrum from "more open" to "more closed" policies. For example, along each dimension, policymakers could decide whether the appropriate goal is

- a completely self-sufficient U.S. capacity
- cooperation with—or, in some cases, dependency on—allied nations only[50]
- cooperation with all nations, except for competitor nations (which the 2022 *National Security Strategy* identifies as China and Russia[51])
- an open global ecosystem.

Although all five areas interact, policymakers do not necessarily need to land at the same place on the spectrum along all five dimensions: Each dimension has distinct considerations, and the most appropriate policy may be more open along some dimensions and more closed along others.[52] But all five of them may benefit from multilateral coordination with other nations.[53]

International Flows of Talent and Research Funding

U.S. research capacity in quantum information science and technology (QIST) would be crippled without international researchers. As discussed above, most Ph.D. students researching quantum-related disciplines in the United States are foreign, as are an even larger majority of post-doctoral researchers. Moreover, these students tend to stay in the United States and contribute their expertise here for a long time after graduation: 72 percent of foreign graduate students in these fields (and 90 percent of Chinese graduate students) still reside in the United States ten years after graduating.[54] Moreover, the U.S. government assesses that, even with these foreign researchers, there is a shortage of talent in QIST in the United States.[55] The flow of talent is not one way: Many U.S. researchers go abroad to other countries as well and acquire valuable skills before (in many cases) returning to the United States.

At the same time, some foreign workers pose a risk to U.S. IP and, in turn, to the advancement of the worldwide development of quantum technology. There has been a concerted effort on the part of other countries to acquire U.S. IP in emerging technologies,[56] and in November 2022 the Office of the Director of National Intelligence launched a "Safeguarding Science" initiative to protect research in these technologies.[57] The U.S. government has specifically stated that "QIST is a target for such malign activity."[58]

To its credit, the U.S. government has carefully considered the trade-offs that are specific to QIST regarding the training of foreign talent in the United States, and the White House NSTC has proposed a balanced strategy that combines openness with appropriate protections.[59] As this strategy points out, the United States will need to both expand its domestic talent base and promote the inward flow of international talent to address its talent shortage. (The 2018 National Quantum Initiative Act specifically focused on strengthening the U.S. domestic talent pool.)

One important question is the degree to which any measures to protect IP should specifically target China, which is generally considered to be the nation that poses the highest threat to U.S. technical IP. The U.S. government's stance on this question has shifted significantly over the past few years. In 2018, the Justice Department launched the China Initiative to counter Chinese economic espionage in the United States.[60] But, with a few exceptions, the China Initiative failed to meet its goals: It led to few convictions in court (and several dismissals and acquittals) and was perceived as having quickly drifted from focusing on major espionage to minor administrative errors by academic researchers.[61] In 2022, the Justice Department admitted that the China Initiative had contributed to a perception that the department was unjustly targeting researchers of Chinese ethnicity, and it shut down the initiative and replaced it with a strategy aimed at a broader range of countries.[62] The 2021 NSTC strategy on foreign talent in quantum does not identify any particular nations as specific threats. The failure of the China Initiative may offer lessons on the risks of focusing on individual nations when countering IP loss.

Given the ubiquity of foreign students in academic quantum technology research in the United States, any attempt to limit professors' ability to hire foreign graduate students would face enormous pushback from the academic community. And because most academic research, by its nature, is eventually published publicly, any such attempts would probably have limited effectiveness in protecting IP. Instead, U.S. government funding agencies have placed increased emphasis on requiring researchers who apply for grants to disclose all other funding sources. This information is a very useful aid to the government's monitoring capability and may be a promising path forward, although the China Initiative's outcomes show that this information is probably a more useful tool for situational awareness than for actual law enforcement.

International quantum R&D funding and talent flow out of the United States as well as into it, and U.S. government funding of foreign research in friendly nations is a promising mechanism for strengthening ties and promoting the exchange of scientific expertise. This already occurs to some degree: For example, the U.S. Air Force Research Lab has offices in several foreign countries, and its Office of Scientific Research jointly funds research in QIST with the National Research Foundation of South Korea.[63] One option for further strengthening ties with other nations could be to establish (and fund) formal bilateral researcher exchanges, in which QIST researchers spend a fixed amount of time working at the other nation's research institutions.

Standard-Setting

The previously esoteric topic of technical standard-setting has recently become an important aspect of geopolitical competition. There is increasing concern within the United States that competitor nations are attempting to influence the international standard-setting process in ways that give them an unfair advantage. The PRC government in particular is explicitly attempting to influence the global standard-setting process as part of its China Standards 2035 plan.[64] It has become a very active participant in international bodies that set standards for several emerging technologies, such as 5G telecommunications, where the standards that the PRC supports could provide Chinese firms with a monopoly on key enabling technologies or could even build in cybersecurity vulnerabilities that Chinese firms could later exploit to collect user data.

Most standard-setting bodies are consortia of private industries, and government policymakers have limited direct influence over them: For example, governments have no legal authority to prohibit any nation from participating in this process. Moreover, most quantum technologies are still too immature for significant standardization. Nevertheless, policymakers should be planning ahead for the standardization process; in particular, they should be prepared for China and other competitor nations to again attempt to influence the standard-setting process (as they did for 5G) and should have a response strategy prepared.

All three categories of quantum technology will eventually need extensive technical standards, but the standard-setting process will look very different among them. Quantum sensors demonstrate a wide variety of possible modalities and applications, but there will likely be a fairly limited set of end users for any given application, perhaps reducing the importance of interoperability standards. Quantum computers will eventually need extensive standards for input-output formats and high-level quantum programming languages, for example.[65] But because quantum sensors and computers cannot yet deliver useful applications, it is probably too soon to begin standardizing them. Benchmarking logically precedes standardization—you need to know the relevant technical requirements and figures of merit for characterizing a given device before you can standardize them—and there are still no widely agreed-upon benchmarks for quantum devices. The Defense Advanced Research Projects Agency (DARPA) is running a program to develop such benchmarks for quantum computers,[66] which will probably need to be established before useful hardware standards can be established.

By their nature, all telecommunication systems depend critically on common standards.

Quantum communications are a very different story. By their nature, all telecommunication systems depend critically on common standards. Also, QKD systems, which have been commercially available since 2007, are the most technically mature quantum technology other than atomic clocks. As mentioned above, the European Union has announced plans to build a continental-scale international QKD network by 2029.[67] As European nations build this network, they will necessarily need to make decisions regarding international standardization, and these decisions could become de facto world standards. Moreover, China has already deployed the world's largest QKD network, which has presumably required Chinese organizations to make complex standardization decisions as well. So far, there has not been any evidence that the Chinese government plans to export this technology beyond its borders, but the history of China's early lead in the deployment of 5G technology suggests that its government may also hope to leverage QKD as a means to dominate another type of high-tech telecommunication infrastructure. Although the U.S. government has expressed doubt about the practical utility of QKD, more-useful quantum communications applications will eventually emerge and will require complex technical standards, and Europe or China could well leverage their experience deploying QKD to take the lead in setting standards for these next-generation technologies as well. How important this development would be for U.S. interests is a challenging question that policymakers will need to wrestle with.

Finally, the United States is developing a countermeasure against the threat that quantum computers will eventually pose to encryption that is very different from QKD, known as *post-quantum cryptography* (PQC).[68] PQC is similar to today's encryption systems in that it allows existing (non-quantum) computers to encrypt information at the software level using mathematical algorithms; unlike today's encryption, however, PQC uses new algorithms that are believed not to be vulnerable even to quantum computers. Following a public analysis by the NSA,[69] the U.S. government determined that it prefers (software-based) PQC over (hardware-based) QKD as a countermeasure against quantum computers' capability to decrypt information. President Joe Biden recently issued a National Security Memorandum ordering the entire U.S. government to upgrade its encrypted communication systems to use PQC by 2035.[70]

Like any communication system, PQC requires precise technical standards. The U.S. government will be following PQC standards that are being developed by the U.S. National Institute of Standards and Technology (NIST).[71] NIST has selected several mathematical algorithms for PQC and plans to release a full encryption standard by 2024. There are no other known efforts to develop PQC standards that are anywhere near as rigorous and open as NIST's, and NIST's eventual standard is widely expected to become the de facto world standard. Nevertheless, many other international standards organizations, such as the United Nations' International Telecommunication Union and the Internet Engineering Task Force, will need to create further standards to implement NIST's PQC encryption standard in lower-level security protocols, such as Transport Layer Security, which is used to secure Hypertext Transfer Protocol Secure (HTTPS)—the ubiquitous padlock that appears in your address bar to indicate that a site is secure.

The worldwide transition to PQC will be a massive logistical effort that could well take decades to complete,[72] and it will require extensive coordination with other countries to ensure that international communication systems remain interoperable. Government policymakers may need to play a role in this coordination, particularly in regard to military communication systems, for which there is not a strong market-driven demand for interoperability. Interoperability between different nations' communication systems is already a serious challenge, especially in the military context,[73] and it will only become more complex as they overhaul their encryption systems. International coordination on the transition to PQC should start well before the new algorithms are adopted. This international coordination should be a high priority of the U.S. government, and it represents one of the most concrete actions that policymakers will need to take with regard to international collaboration in quantum-related technology.

More broadly, it would be helpful for allied nations to more clearly articulate whether they plan to adopt QKD, PQC, or both to respond to the quantum threat to decryption. The U.S., UK, and French governments have publicly stated that they plan to adopt only PQC and not QKD, particularly for national security systems.[74] But no other allied nations have clearly articulated a position on the relative merits of these countermeasures. At least one NATO member's military, Portugal's Armed Forces General Staff, is investing in R&D toward using QKD to secure military communications.[75] A future in which some NATO countries are using hardware-based encryption systems and others are using software-based encryption systems would pose severe challenges to military interoperability. U.S. policymakers may want to consider privately encouraging their allied counterparts (particularly, allied militaries) to clarify their positions on the adoption of QKD and/or PQC.

Supply Chains

Supply chain resilience has become an increasingly urgent U.S. government priority, given both the massive disruption to global supply chains caused by the coronavirus disease 2019 (COVID-19) pandemic and the tense geopolitical relations with China, a major U.S. supplier of both low-tech and high-tech equipment. One of President Biden's first actions after taking office was to order a comprehensive 100-day review of the U.S. supply chains for critical products, such as semiconductors, batteries, and pharmaceuticals.[76]

As quantum technologies become more mature and production scales up, the supply chains for quantum devices will become an increasingly important policy issue.

As quantum technologies become more mature and production scales up, the supply chains for quantum devices will become an increasingly important policy issue.[77] These supply chains are unusually difficult to assess because several very different physical approaches are being pursued in parallel that require very different critical components and materials, and it is unlikely that all of these approaches will remain relevant in the long run.

This heterogeneity of approaches is most concrete with regard to quantum computing, where different organizations are pursuing largely unrelated qubit technology approaches. For example, within one of the leading qubit technology approaches, superconducting-transmon qubits need to be cooled down to within one-thousandth of a degree of absolute zero using a very complex device known as a *dilution refrigerator* (the best of which are currently made in Finland).[78] But another leading qubit technology approach uses trapped-ion qubits and does not use dilution refrigerators at all, but instead requires very high-quality lasers (primarily made in Japan) and isotopically pure samples of various elements—neither of which are used with superconducting-transmon qubits. This technological uncertainty means that, in ten years, dilution refrigerators might be a critical link in the quantum supply chain, or they might be completely irrelevant.[79]

The supply chains for quantum technologies are therefore very complex and will change rapidly as the technologies mature, and there have only been a few public systematic studies of them so far.[80] For our 2022 report, I and other RAND researchers spoke with representatives from nine U.S. quantum technology companies about their supply chains, and we found that they used several critical components and materials that could only be sourced from small companies in Europe and Japan. These U.S. companies bought many commercial off-the-shelf commodities from China for cost-saving reasons, but we did not identify any critical U.S. supply chain dependencies on either China or Russia, or even any components for which those nations were competitive on quality (as opposed to price). But this could certainly change if China improves its high-tech manufacturing capacity. Moreover, many of the small start-ups that we spoke with did not have the capacity to perform the extensive supply chain monitoring and risk management that large corporations do, so they were unable to determine their critical suppliers at deeper tiers of their supply chains, which leaves open the possibility that the United States already has critical dependencies on competitor nations for quantum technology components.[81]

A completely domestic U.S. supply chain that covers all promising technologies would be extremely expensive and probably infeasible for the foreseeable future, given the large number of non-overlapping components in play, the uncertainty in terms of which components will prove important in the long term, and the fragmented nature of the supplier companies. Policymakers will therefore need to decide what degree of dependence on allied or partner nations is acceptable. In principle, a group of nations could negotiate a formal top-down agreement that each nation would maintain a competitive production capacity for certain critical quantum components, but such an aggressive industrial policy is politically unrealistic (not to mention logistically challenging and possibly technologically counterproductive). A more realistic model might be a looser international forum for coordinating supply chains, somewhat like the "Chip 4" initiative that the United States, South Korea, Japan, and Taiwan launched to help maintain a reliable semiconductor supply chain that does not include the PRC.[82] But the Chip 4 initiative has faced serious internal challenges, indicating the difficulty of making such an international technology alliance successful.

A more unilateral (and logistically easier) course of action would be for the U.S. government to identify a few key components for which it wants the United States to retain production capacity and to promote domestic production of these components via (for example) the Small Business Innovation Research or Small Business Technology Transfer programs, which fund small businesses to perform R&D in specific areas. Many of the supplying companies are quite small and financially vulnerable to economic downturns, so the federal government has some leverage to affect their demand stream. In this regard, the quantum industry is very different from massive and mature tech industries, such as solar panels or smartphones, for which the private commercial market swamps the federal government's buying power.

Policymakers can also take less direct steps to strengthen the supply chain for quantum technologies. For example, the 2018 National Quantum Initiative Act established the Quantum Economic Development Consortium (QED-C) of U.S. industry and academic stakeholders in quantum technology. One of its main purposes is to "enable and support a robust U.S. . . . quantum industry supply chain" by performing industry analysis, facilitating information-sharing between stakeholders, and presenting a unified voice of industry positions to the government.[83] In June 2022, the QED-C opened its membership to 36 allied and partner nations;[84] moving forward, it will probably provide a useful conduit for unofficial diplomacy and industry cooperation between the United States and friendly nations. Several allied nations have established similar national quantum technology industry consortia, which could also perform useful coordinating functions.[85]

Export Controls

Export controls have become an increasingly popular foreign policy tool for managing international technology competition. In October 2022, the Biden administration imposed tough new export controls on the sale of computing and semiconductor equipment to the PRC.[86] These new controls have proven quite effective at disrupting China's production capacity: Major suppliers such as ASML have suspended work at Chinese chip factories, and experts believe that the impact will be long-lasting.[87]

The United States has already imposed controls on exporting quantum technology to several specific Chinese and Russian organizations. In October 2020, the White House designated quantum information science as one of 20 Critical and Emerging Technologies that must be "adequately controlled under export laws and regulations."[88] In November 2021, the Commerce Department added three PRC quantum technology organizations to its Entity List of foreign organizations to which any U.S. exports are prohibited.[89] In March 2022, it added a Russian quantum technology company in response to Russia's invasion of Ukraine.[90] In September 2022, the Treasury Department toughened these sanctions by prohibiting the U.S. supply "of quantum computing services to any person located in the Russian Federation."[91] President Biden also issued an executive order directing the Committee on Foreign Investment in the United States to consider all proposed investments' "effect on U.S. technological leadership in areas affecting U.S. national security, including . . . quantum computing" (although this is not an export control per se).[92] National Security Advisor Jake Sullivan has described export controls as a key new tool for national security while specifically identifying quantum information science as a key national security technology,[93] and the administration is reportedly considering further controls on exporting quantum computing technology to the PRC.[94]

All technology export controls have some risk of being ineffective, if nations outside the export-control regime continue to develop their technology by finding alternatives to the United States for supplies or technical expertise. Worse, export controls could backfire by prompting the excluded nations to develop their own production capability.

Export controls for quantum technology are even more challenging to craft, for the same reason that the supply chain is difficult to protect: There are huge uncertainties in both the eventual applications of quantum technology and the most-promising technical approaches (and therefore the critical components). No one yet knows which quantum devices will pose risks to U.S. national security or the most effective way to deny those devices to adversary nations. Much quantum technology R&D is still in the scientific research stage; even many private companies are still describing their technological progress in detail in the open scientific literature. As discussed above, the QIST enterprise is highly international and depends on the flow of scientific ideas across borders. There is a serious risk that export controls might prematurely stifle the scientific advancement of quantum technology, which has not yet demonstrated any clear commercial applications (other than atomic clocks). It is also not clear whether the United States would be exporting any quantum technology to China or Russia, now or in the foreseeable future, even in the absence of any export controls, so it is hard to tell whether these controls are having any effect.

Moreover, the many recently founded quantum technology start-ups do not have any clear revenue streams for the foreseeable future. The sharp increase in interest rates in 2022 and the significant risk of an economic recession in 2023 will make it challenging for these companies to raise money from private investors, so their financial situation is not stable. Export controls could further damage their economic prospects and could backfire by damaging the U.S. domestic quantum industry. Most of the quantum start-ups that we spoke with for our 2022 RAND report expressed serious concern over potential export controls, and some described the prospect of export controls as an existential threat.[95]

But there are important differences among the categories of quantum technology with regard to export controls. Table 1 lists some key questions for policymakers to consider, along with preliminary answers for each category of quantum technology, with each "Probably" or "Maybe" strengthening the case for export controls.

Table 1 suggests that the case for export controls on quantum sensors is stronger than the case for export controls on quantum computers, because the national security applications of quantum sensors are clearer and more easily separable from peaceful applications. Indeed, quantum sensors are the only category of quantum technology that already has broad export controls in place.[96]

Policymakers will need to wrestle with many other challenging issues involving export controls on quantum technology, such as the following:

1. *If export controls are imposed, should they be at the component level or at the level of integrated systems (e.g., functional quantum sensors or computers)?* The uncertainty in the critical components and eventual applications would tend to favor the system level. But, as discussed above, few useful quantum systems exist, and the relevant technical benchmarks for characterizing them are not clear, so system-level export controls would be challenging to impose at this time.
2. *How should export controls apply to remote cloud access from abroad to quantum computers physically located in the United States?* Very few quantum computers have been physically sold so far; the vast majority of end users currently access a small number of quantum computers via the cloud. Should export controls apply to the international

TABLE 1

Key Policy Considerations for Export Controls on Categories of Quantum Technology

Question	Quantum Computing	Quantum Communications	Quantum Sensing
Can policymakers identify specific national security applications that will soon become technically feasible?	No	No	Maybe
Can policymakers craft export controls that will apply only to the national security applications and not to the civilian applications?	No	No	Maybe
Do policymakers know which critical components will be necessary for a competitor nation to build a useful quantum technology system?	No	Probably	Probably
Does the United States control the supply chain for the critical components today?	No	No	No
Would the impact of export controls on critical components be confined to just quantum technology without affecting other industries?	Depends on the qubit technology	Maybe	Probably

NOTE: The assessments in this table are not intended to be quantitatively precise, but "Maybe" notionally corresponds to a roughly 50 percent probability, whereas "Probably" notionally corresponds to a probability that is significantly higher than 50 percent (but significantly lower than 100 percent).

transmission of the outputs of a quantum computer's calculations?

3. *How will export controls apply to foreign nationals who are physically located in the United States?* The current U.S. legal framework for export controls contains unique provisions that restrict *deemed exports*, which refers to the release of restricted information to a foreign national living in the United States. Depending on how export controls are crafted, deemed export provisions might significantly affect U.S. quantum technology companies that employ foreign nationals. If their inclusion criteria are broad enough to cover the quantum devices or technical information used for scientific research performed at universities, then deemed export provisions could seriously affect the large proportion of U.S. academic quantum research groups that employ foreign graduate students or postdoctoral fellows.
4. *Should the export controls be unilateral or multilateral?* Because the United States does not have full control over any quantum technology supply chains today (and considering the highly international nature of quantum R&D), export controls may need to be multilateral to be effective. But the more nations that are included in a multilateral export control regime, the more challenging the political, bureaucratic, and logistical considerations become. A multilateral export control regime would probably not be agile enough to quickly adapt to such a rapidly changing technology as quantum.

Any policy decisions regarding export controls should be informed by input from industry stakeholders, perhaps through the QED-C or other government-facing industry

> At this early stage of high technical uncertainty, covering as many bases as possible is arguably more important than excelling at any one approach.

consortia. Of course, private companies have somewhat different priorities and incentives than government policymakers; in most cases, these priorities will probably lead industry to oppose export controls by default. Nevertheless, as the main nongovernment groups with a stake in export control policy, companies will bring extensive technical expertise, as well as the best experience-driven understanding of how export controls would play out in practice. They should therefore be involved in discussions related to export controls in order to inform (but not determine) policy decisions.

Before imposing broad export controls, policymakers should have a coherent strategy that offers a clear goal and addresses these questions. Improperly targeted export controls that excessively affect allied nations could damage international relations and slow global scientific progress. In principle, a carefully calibrated (and potentially multilateral) export control regime might strengthen ties with U.S. allies while slowing competitor nations' progress toward developing technologies that could harm U.S. national security—but it is not at all clear that threading this needle would be possible in practice.

Technology Approach Diversification

As discussed above, many fundamentally different physical approaches to building quantum devices are being pursued in parallel across the world.[97] A common underlying cause of many of the complexities discussed above is that scientists do not yet know which basic technical approaches may prove useful in the long term, so it is very difficult to assess the status quo.

At this early stage of high technical uncertainty, covering as many bases as possible is arguably more important than excelling at any one approach. The United States is in a strong position of broad technology leadership: It is the world leader in most quantum technology approaches, and U.S. policymakers have determined that the relatively few technical areas in which the United States does not lead (such as QKD) are not strategic priorities.[98] As recommended in our 2022 report, U.S. policymakers should therefore continue to broadly fund quantum science research across a wide range of technology approaches in order to maintain overall global scientific leadership.[99]

No one nation can feasibly lead in every aspect of a field as complex and diverse as quantum technology, so there are inevitably some areas in which other nations are ahead of the United States. But the United States has a huge advantage over strategic competitors like China and Russia: It has a large network of close and technologically advanced allied and partner nations, and China and Russia do not. This network gives the United States access to many more technology developments than occur within U.S. borders, and the U.S. government should take advantage of it. As the relevant technical benchmarks become clearer, policymakers should systematically track the most technically advanced nations across all leading candidate technical approaches and applications. (Of course, policymakers will need to leverage internal technical expertise to make expert judgments as to when a technical approach or application is so far from utility that it is no longer worth focusing on, as the U.S. government has already done for quantum radar and QKD.[100])

A spur for policy action could be if policymakers determine that *no* allied nations have globally cutting-edge technical capacity in some promising technical approach. In this case, policymakers should consider investing focused R&D into building domestic capacity in that approach. This targeted investment might be done in formal coordination with allied nations, but practically speaking, such coordination is unlikely—there are few relevant precedents. Government policymakers (in consultation with internal technical experts) may eventually determine that certain specific technology approaches or applications are so critical to economic prosperity or national security that the United States needs to maintain a completely domestic capacity. But there are not yet any applications that clearly justify the likely high costs of doing so.

Information-sharing among allies and partners is more achievable than formal investment coordination and is arguably just as valuable. Simply knowing which nations are working on (and excelling at) which technical approaches would be very useful for setting appropriate U.S. policy on quantum technology. Such information-sharing could be formalized in several ways. One possibility would simply be to hold a regularly scheduled global conference at which technical experts from multiple allied or partner nations' governments meet and exchange technical progress and priorities. Another possibility would be to have each nation's government regularly perform a detailed self-assessment of internal technical capabilities in quantum science and technology—ideally, in a standardized format with a documented methodology—which would be shared among national governments. (Such an international conference or shared self-assessments probably should not be public to allow for a frank exchange of potentially sensitive information and to avoid becoming an exercise in industry marketing.) National governments certainly will not have full visibility into private industry activity within their nations, but they will generally have a better understanding than their allies' governments will. Also, technology diversification is most important for early-stage technologies that are still undergoing basic science research; because national governments are usually the main funders of basic research, they have better awareness of the status of these early-stage technologies than of more-mature technologies.

At the very least, policymakers should encourage technical experts within government to attend international academic and industry conferences. These conferences would not only advance the experts' scientific understanding but would also help them maintain awareness of technical progress by other nations—not just by competitors but, just as importantly, by allies and partners.

A Proposal for a Desired End State for Quantum Technology R&D

The previous section illustrated how complex and multidimensional the policy space around international collaboration in quantum R&D is. Even without comprehensively covering all the relevant policy issues, it illustrated that there are at least five major independent (but interconnected) axes along which policymakers need to decide how open or closed the United States should be regarding its inputs and outputs of quantum R&D. Ideally, policymakers would choose some well-specified desired end state to determine the optimal position in the policy space. In this final section, I step back and propose a desired strategic end state for the U.S. quantum ecosystem that may help provide a unifying framework for how policymakers should think about the many interconnected policy decisions in this space. I make no claim that this proposed end state is self-evidently the best one for policymakers to target; policymakers may prefer an end state in which the United States is either more self-sufficient in the quantum R&D area or more interconnected with its allies and partners (or even its competitors). Hopefully, this proposal offers a useful starting point for setting more-specific supporting goals.[101]

The proposed end state is as follows: **Until applied quantum technology reaches the stage of technical maturity at which its concrete applications become clear, the United States maintains access to the global cutting edge of every quantum technology application that could plausibly significantly improve its economic well-being or national security.**

At first, this proposed end state may sound incredibly ambitious. It might be read as suggesting that "the United States must be the best at absolutely every aspect of quantum technology." But in fact, it is much more limited in scope, and I believe that it offers a reasonable and realistically achievable balance of ambition and pragmatism.

To clarify the scope of this proposed end state, it may be helpful to explain what it does *not* imply, as follows:

- The proposed end state does not imply that the United States must lead in the development of every area of applied quantum technology. It would be acceptable if an allied or partner nation were ahead of the United States in certain capabilities, as long as the U.S. government is confident that it will maintain access to those capabilities. (Depending on the nature of the technology, "maintaining access" might entail, for example, being able to purchase a sufficient quantity of quantum devices and having enough domestic expertise to be able to operate them. Or it might mean accessing an allied nation's cloud quantum computing servers from the United States.[102]) Taken together—although not individually—the United States and its allies match or dominate the U.S. strategic competitors on most relevant fronts, including population, economic output, and scientific output. Strong ties and technology-sharing among allied and partner nations are therefore critical for achieving this proposed end state.
- The proposed end state does not imply that the United States must have access to every demonstrated quantum technology. There are several quantum technology applications, such as QKD and quantum radar, that the U.S. government has publicly determined are unlikely to lead to strategic

capabilities that outmatch non-quantum technology.[103] It is acceptable to cede R&D leadership in these applications to other nations. If U.S. technical experts are sufficiently confident that these applications will not be directly useful (and will not lead to indirect benefits, such as transferable technical expertise), then it would even be acceptable to cede technical leadership in these applications to competitor nations.

- The proposed end state does not imply that the United States must be the leader in every basic scientific approach being researched. The U.S. government's understanding of the technical trade space may eventually reach the point where its experts can assess that certain scientific *approaches* (as opposed to target applications) are unlikely to be strategically important, even if they may be scientifically interesting.[104] It would be acceptable to cede scientific leadership in these approaches to other nations—even to competitor nations, if the U.S. government is sufficiently confident in its expert assessment.

To be clear, this proposed end state is (appropriately) ambitious. If the United States successfully achieves it—which is not guaranteed—then the United States could benefit from potentially enormous new economic and national security advantages. In almost any scenario in which the United States achieves this end state, it will continue to be the world's leading nation in quantum technology taken as a whole, although not necessarily in every specific application.

Ceding scientific leadership in *any* quantum technology to competitor nations may seem unacceptably risky. But over the coming decades, the United States will face increasing budgetary pressure as its population continues to age and its social safety net spending increasingly crowds out discretionary budget priorities. The United States will probably not have the option of being the sole scientific leader in every technical area of QIST, particularly as QIST competes for scientific funding with other strategic technologies, such as AI, microelectronics, biotech, and clean energy. Policymakers will need to make tough R&D prioritization decisions, which may include ceding leadership in certain technical areas.

Policymakers will need to make tough R&D prioritization decisions, which may include ceding leadership in certain technical areas.

The quantum technology landscape will look very different in coming years as the world gains a better understanding of the most-promising scientific approaches, practical applications, and industry structure in a mature quantum ecosystem. Eventually, policymakers will need to set more fine-grained and more quantitatively precise intermediate goals. But such a mature ecosystem is still many years (potentially, decades) out. Patience, flexibility, broad-based situational awareness, and responsiveness to technology surprise will be the keys to successful quantum technology policy for the foreseeable future.

Notes

[1] White House, "Remarks by National Security Advisor Jake Sullivan at the Special Competitive Studies Project Global Emerging Technologies Summit."

[2] White House, *National Security Strategy*. In this Perspective, I use the term *ally* to refer to nations that have signed formal treaties of alliance with the United States. I use the term *partner* to refer to nations with whom the United States cooperates based on policy goals that are aligned in the near term but without a presumption that such cooperation will continue indefinitely.

[3] American Academy of Arts and Sciences, *America and the International Future of Science*; Matthew P. Goodman and Brooke Roberts, "Toward a T12: Putting Allied Technology Cooperation into Practice."

[4] Stew Magnuson, "The Quad: Creating a Defense Tech Alliance to Stand Against China."

[5] Alexander Wirth, "Building the Transatlantic Tech Alliance."

[6] I do, however, draw on significant technical background and previous policy research for some of the analytic assessments regarding policy-relevant differences between the subcategories of quantum computing, sensing, and communications.

[7] U.S. Department of Defense, "2022 National Defense Strategy."

[8] Josh Horwitz, "Xi's Call to Win Tech Race Points to New Wave of Chinese State-Led Spending."

[9] Will Knight, "The US Throws $52 Billion at Chips—but Needs to Spend It Wisely."

[10] Will Thomas, "National Quantum Initiative Signed into Law."

[11] Anshu Siripurapu and Noah Berman, "Is Industrial Policy Making a Comeback?"

[12] "Many Countries Are Seeing a Revival of Industrial Policy."

[13] Reda Cherif and Fuad Hasanov, *The Return of the Policy That Shall Not Be Named: Principles of Industrial Policy*.

[14] Chris Buckley, "Xi's Post-Virus Economic Strategy for China Looks Inward."

[15] Gibson Dunn, "United States Creates New Export Controls on China for Semi-Conductor Manufacturing Technology, Advanced Semiconductors, and Supercomputers in New Phase of Strategic Tech Competition."

[16] Subcommittee on Quantum Information Science, Committee on Science, National Science and Technology Council, *National Strategic Overview on Quantum Information Science*, p. 4. There are slightly technical nuances between the terms *quantum technology* and *quantum information science*, but these terms are used interchangeably in this Perspective.

[17] The U.S. government generally uses the term *international agreement* to refer to a commitment that is legally binding under international law and uses such terms as *joint statement* to refer to nonbinding statements of policy.

[18] The joint statement with South Korea covers other technologies as well but specifically discusses quantum. See U.S. Department of State, "Tokyo Statement on Quantum Cooperation"; U.S. Department of State, "Joint Statement of the United States of America, United Kingdom, and Northern Ireland: Cooperation in Quantum Information Sciences and Technologies"; U.S. Department of State, "Joint Statement of the United States of America and Australia: Cooperation in Quantum Science and Technology"; U.S. Department of State, "Joint Statement of the United States and Finland on Cooperation in Quantum Information Science and Technology"; U.S. Department of State, "Joint Statement of the United States of America and Sweden on Cooperation in Quantum Information Science and Technology"; U.S. Department of State, "Joint Statement of the United States of America and Denmark on Cooperation in Quantum Information Science and Technology"; U.S. Department of State, "Joint Statement of the United States of America and Switzerland on Cooperation in Quantum Information Science and Technology"; White House, "United States–Republic of Korea Partnership"; White House National Quantum Coordination Office, "The United States and France Sign Joint Statement to Enhance Cooperation on Quantum."

[19] White House, "Quad Joint Leaders' Statement."

[20] White House, "Implementation of the Australia–United Kingdom–United States Partnership (AUKUS)."

[21] Edward Parker, *Commercial and Military Applications and Timelines for Quantum Technology*; Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*; White House National Quantum Coordination Office, *Quantum Frontiers: Report on Community Input to the Nation's Strategy for Quantum Information Science*.

[22] NSA, "Post-Quantum Cybersecurity Resources."

[23] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*.

[24] Elizabeth Gibney, "Quantum Gold Rush: The Private Funding Pouring into Quantum Start-Ups"; Chris Jay Hoofnagle and Simson Garfinkel, "What If Quantum Computing Is a Bust?"

[25] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. Except where otherwise cited, all findings in the rest of this section are drawn from this source.

[26] There are multiple technology approaches to quantum computing being developed in parallel, and although the United States maintains leadership in most of them, China has reached rough parity in building prototype quantum computers that use superconducting-transmon qubits, which is arguably the leading technical approach today. The United States and China are the only two nations to have demonstrated prototype quantum computers capable of performing a calculation faster than the world's most powerful non-quantum supercomputers (Frank Arute et al., "Quantum Supremacy Using a Programmable Superconducting Processor"; Yulin Wu et al., "Strong Quantum Computational Advantage Using a Superconducting Quantum Processor").

[27] In this Perspective, I use the term *technical approach* to refer to how quantum devices physically work at the technical level and the term *application* to refer to the useful task that they are designed to achieve. The same technical approach could enable multiple applications; conversely, many different technical approaches could each enable the same application.

[28] Edward Parker, *Commercial and Military Applications and Timelines for Quantum Technology*; Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*.

[29] Yu-Ao Chen et al., "An Integrated Space-to-Ground Quantum Communication Network over 4,600 Kilometres."

[30] NSA, "Quantum Key Distribution (QKD) and Quantum Cryptography (QC)." The NSA acknowledges the serious threat that quantum computers will eventually pose to information security, but it prefers a different countermeasure, known as *post-quantum cryptography*, which is discussed in a later section.

[31] Subcommittee on Quantum Information Science, Committee on Science, National Science and Technology Council, *A Coordinated Approach to Quantum Networking Research*, pp. 4 and 6.

[32] Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, National Science and Technology Council, *The Role of International Talent in Quantum Information Science*.

[33] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*.

[34] Patries Boekholt et al., *Drivers of International Collaboration in Research*.

[35] Alison K. Hottes et al., *International Basic Research Collaboration at the U.S. Department of Defense: An Overview*.

[36] John P. Holdren, "How International Cooperation in Research Advances Both Science and Diplomacy."

[37] U.S. Department of Defense, "2022 National Defense Strategy"; White House, "Remarks by President Biden on America's Place in the World."

[38] Caroline S. Wagner, "International Collaboration in Science and Technology: Promises and Pitfalls," p. 167.

[39] These nominal costs are not directly comparable because they extended across different periods and over long enough periods that inflation significantly changed the value of the currency over the course of each project (European Space Agency, "How Much Does It Cost?"; Alex Knapp, "How Much Does It Cost to Find a Higgs Boson?"; National Human Genome Institute, "Human Genome Project").

[40] Mark A. Lorell, *Troubled Partnership: A History of U.S.-Japan Collaboration on the FS-X Fighter*.

[41] One possible successful example was the UK's technical cooperation with the United States in developing the UK strategic nuclear deterrent during the Cold War. An initial joint U.S.-UK R&D program, "Skybolt," was canceled in 1962, but it was followed by a successful "Polaris" program, which used U.S.-built missiles that housed warheads designed in the UK with U.S. collaboration. Another example was the XM982 Excalibur 155mm artillery projectile, which was codeveloped from 1999 to 2002 under a U.S.-Swedish R&D project arrangement. However, both of these programs involved technologies that were already much more mature than quantum technology is today, and they involved system engineering and integration more than basic (or even applied) research (Joseph S. Minus, Jr., and Lu Ting, "Precision Acquisitions—Sharing the Lessons of Excalibur"; Parliament of the United Kingdom, *Select Committee on Defense Eighth Report*).

[42] One interesting exception to this pattern is the International Thermonuclear Experimental Reactor (ITER), a 35-nation collaboration to develop fusion power that is still in the basic research stage. ITER does not intend to begin plasma experiments until late 2025, so it is too early to know whether the project will succeed or fail. But the early signs have not been particularly encouraging: The project has faced management challenges and cost overruns, as well as skepticism on technical grounds, and a U.S. national laboratory recently beat ITER to its goal of breakeven fusion ignition (Breanna Bishop, "National Ignition Facility Achieves Fusion Ignition"; Henry Fountain, "A Dream of Clean Energy at a Very High Price"; A. Hassanein and V. Sizyuk, "Potential Design Problems for ITER Fusion Device").

[43] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. As discussed later, the U.S. government restricts exports of other quantum technologies to specific *entities*, but it only places blanket export controls at the *technology* level on quantum sensors.

[44] European Commission, "The Future Is Quantum: EU Countries Plan Ultra-Secure Communication Network."

[45] Craig Gidney and Martin Ekerå, "How to Factor 2048 Bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits."

[46] Ryan Babbush, "The Quest for Viable Quantum Algorithms and Applications."

[47] Although as Wagner discusses, there also can be bottom-up but centralized scientific collaborations (Caroline S. Wagner, "International Collaboration in Science and Technology: Promises and Pitfalls").

[48] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*.

[49] An interesting sixth area of potential international collaboration could be developing a uniform ethical framework for the deployment of quantum technologies, similar to the 1975 Asilomar Conference on Recombinant DNA, which led to a voluntary framework limiting certain uses of recombinant DNA that were deemed ethically irresponsible. But this is less likely to be an area of active governmental policymaking for the foreseeable future. Most conversations related to ethics in quantum technology have focused on having diverse and inclusive workforces and access to quantum technology, which are issues most likely to be addressed at the national or subnational level or by nongovernmental organizations. The most plausible point of ethical discussion in terms of the technical applications of quantum technology would concern the deployment of quantum computers that are capable of breaking decryption. However, given the huge national security implications and the direct and concrete near-term benefits and harms of this application, coming to an international consensus on the appropriate ethical use of this technology would be very challenging. The United States and its European allies have already demonstrated very different perspectives on internet privacy through such regulations as Europe's General Data Protection Regulation. Also, nations probably would not trust that other nations are not secretly using this capability once it becomes technically feasible. That said, international nongovernmental organizations could adopt ethical policies that are not legally binding, such as the World Economic Forum's 2022 report on quantum computing governance principles (World Economic Forum, *Quantum Computing Governance Principles*).

[50] In which case, the set of allied nations needs to be determined, such as only the defense Technical Cooperation Program members, or all treaty allies, including all 30 NATO members (Australian Department of Defence, "The Technical Cooperation Program").

[51] White House, *National Security Strategy*.

[52] It is worth noting that a 2022 report from the National Academies recommends that U.S. policymakers prioritize strengthening domestic innovation via an open research environment and shift away from restricting competitor nations' technology access (National Academies of Sciences, Engineering, and Medicine, "Maintaining U.S. Global Leadership in Science and Technology Requires Greater Focus on Strengthening Innovation, Not Solely on Restricting Access to Specific Technologies").

[53] Harry G. Broadman and Chaouki Abdallah, "G7: Balance Security and Collaboration."

[54] Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, National Science and Technology Council, *The Role of International Talent in Quantum Information Science*.

[55] Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, National Science and Technology Council, *The Role of International Talent in Quantum Information Science*.

[56] National Bureau of Asian Research, *Update to the IP Commission Report*; Strider Technologies, *The Los Alamos Club: How the People's Republic of China Recruited Leading Scientists from Los Alamos National*

Laboratory to Advance Its Military Programs; White House Office of Science and Technology Policy, “Enhancing the Security and Integrity of America’s Research Enterprise.”

[57] Office of the Director of National Intelligence, “Safeguarding Science.”

[58] Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, National Science and Technology Council, *The Role of International Talent in Quantum Information Science*, pp. 9–10.

[59] Subcommittee on Economic and Security Implications of Quantum Science, Committee on Homeland and National Security, National Science and Technology Council, *The Role of International Talent in Quantum Information Science*.

[60] Federal Bureau of Investigation, “Executive Summary: China: The Risk to Corporate America.”

[61] Michael German and Alex Liang, “Amid New Trial, End of Chinese Espionage ‘Initiative’ Brings Little Relief to US Academics Caught in Net of Fear.”

[62] Ellen Nakashima, “Justice Department Shutters China Initiative, Launches Broader Strategy to Counter Nation-State Threats.”

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[64] ChinaFile, “Will China Set Global Tech Standards?”; Valentina Pop, Sha Hua, and Daniel Michaels, “From Lightbulbs to 5G, China Battles West for Control of Vital Technology Standards.”

[65] Some companies have already developed their own (relatively) high-level programming languages, such as IBM’s Qiskit and Microsoft’s Q#, but these languages are nowhere near as widely used, nor as precisely and formally standardized, as (for example) the C++ programming language.

[66] DARPA, “Quantum Benchmarking (QB).”

[67] European Commission, “The Future Is Quantum: EU Countries Plan Ultra-Secure Communication Network.”

[68] PQC is sometimes also referred to as *quantum-resistant cryptography*.

[69] NSA, “Quantum Key Distribution (QKD) and Quantum Cryptography (QC).”

[70] Strictly speaking, this memorandum only covered public-key encryption, not symmetric-key encryption (Joseph R. Biden, Jr., “National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems”).

[71] National Institute of Standards and Technology, “Post-Quantum Cryptography.”

[72] Michael J. D. Vermeer and Evan D. Peet, *Securing Communications in the Quantum Computing Age: Managing the Risks to Encryption*.

[73] Rodney Fogg et al., “Interoperability: Embrace It or Fail!”

[74] Agence Nationale de la Sécurité des Systèmes d’Information, “Should Quantum Key Distribution Be Used for Secure Communications?”; National Cyber Security Centre, “Quantum Security Technologies”; NSA, “Quantum Key Distribution (QKD) and Quantum Cryptography (QC).”

[75] Discretion, homepage.

[76] White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth*.

[77] Manoj Harjani and Shantanu Sharma, “Will Quantum Supply Chains Fall Victim to Geopolitics?”

[78] Depending on the design, dilution refrigerators require various amounts of liquid helium, which is in increasingly scarce supply worldwide and faces demand competition with medical applications, such as magnetic resonance imaging (MRI).

[79] Similarly, high-quality fiber-optic cabling is important for quantum communications but less so for some quantum computing technologies. Many quantum sensors require high-quality lasers, but some of these lasers operate at completely different frequencies and are sourced separately from those used for quantum computers.

[80] National Academies of Sciences, Engineering, and Medicine, *Domestic Manufacturing Capabilities for Critical DoD Applications: Emerging Needs in Quantum-Enabled Systems—Proceedings of a Workshop*; Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*; Bob Sorensen and Tom Sorensen, “Challenges and Opportunities for Securing a Robust US Quantum Computing Supply Chain.”

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[82] Christian Davies et al., "US Struggles to Mobilise Its East Asian 'Chip 4' Alliance."

[83] Quantum Economic Development Consortium, "Purposes."

[84] Quantum Economic Development Consortium, "QED-C® Expands Membership to More Than 36 Countries."

[85] The QED-C also lists "guid[ing] standards and regulation" as one of its priorities. It is not yet clear to what extent technical standards will be directly set by the QED-C, rather than by more-established and general-purpose standard-setting bodies, such as the International Telecommunication Union, Internet Engineering Task Force, and the International Organization for Standardization. Regardless, the QED-C will be an important source of technical and industry expertise that should inform the policy decisions related to standardization that were discussed above.

[86] Bureau of Industry and Security, Department of Commerce, "Commerce Implements New Export Controls on Advanced Computing and Semiconductor Manufacturing Items to the People's Republic of China (PRC)."

[87] Jeanne Whalen, "Western Suppliers Cut Ties with Chinese Chipmakers as U.S. Curbs Bite."

[88] White House, "National Strategy for Critical and Emerging Technologies," p. 9.

[89] Bureau of Industry and Security, Department of Commerce, "Addition of Entities and Revision of Entries on the Entity List; and Addition of Entity to the Military End-User (MEU) List," p. 67317.

[90] Bureau of Industry and Security, Department of Commerce, "Implementation of Sanctions Against Russia Under the Export Administration Regulations (EAR)," p. 12226.

[91] U.S. Department of the Treasury, "Treasury Targets Additional Facilitators of Russia's Aggression in Ukraine."

[92] Joseph R. Biden, Jr., "Executive Order on Ensuring Robust Consideration of Evolving National Security Risks by the Committee on Foreign Investment in the United States."

[93] White House, "Remarks by National Security Advisor Jake Sullivan at the Special Competitive Studies Project Global Emerging Technologies Summit."

[94] Anna Edgerton et al., "US Eyes Expanding China Tech Ban to Quantum Computing and AI."

[95] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology.*

[96] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology.*

[97] The following are just a few examples of the many alternative technical approaches being pursued:

- in quantum computing, superconducting-transmon vs. trapped-ion vs. neutral-cold-atom vs. photonic vs. silicon-spin quantum dot vs. topological qubits; gate-based universal computing vs. adiabatic computing vs. direct quantum emulation vs. quantum annealing vs. boson sampling; noisy intermediate-scale quantum vs. fault-tolerant architectures.
- in quantum communications, fiber vs. satellite vs. underwater vs. atmospheric free-space transmission; prepare-and-measure QKD vs. entanglement-based QKD vs. quantum device networking; various quantum memory architectures; spontaneous parametric down-conversion vs. quantum dot entanglement generation.
- in quantum sensing, Rydberg atoms vs. Bose-Einstein condensates vs. nitrogen-vacancy sensors.

[98] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology.*

[99] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology.*

[100] Defense Science Board, *Applications of Quantum Technologies: Executive Summary.*

[101] The planning method known as *backcasting* offers one useful methodology for translating a desired end state into concrete policies to help achieve it, although the formal application of backcasting to this proposed end state is outside the scope of this Perspective (John B. Robinson, "Futures Under Glass: A Recipe for People Who Hate to Predict").

[102] Whether the United States can maintain access will depend on more than just the strength of the diplomatic relationship between the U.S. government and the allied nation's government. It could also depend on the allied nation's legal systems, trade agreements, political ideology, etc.

[103] Defense Science Board, *Applications of Quantum Technologies: Executive Summary.*

[104] For example, the U.S. government might eventually conclude that certain types of qubits under exploration cannot be scaled up enough to enable useful quantum computers.

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About This Perspective

Quantum technology is still at an early stage of maturity, but it could eventually have major impacts on both economic prosperity and national security. Many U.S. allied and partner nations have strong technical capacity in quantum research and development, and effective collaboration will be critical for keeping the United States and its allies and partners competitive with other nations that are also investing significant resources into this area. This Perspective gives a broad and mostly nontechnical overview of the current quantum technology landscape and the strategic importance of (and challenges of) research collaboration with allied and partner nations. This Perspective also includes a discussion of five key policy areas in this space—talent flows, standard-setting, supply chains, export controls, and technology approach diversification—and concludes with a proposal for a desired strategic end state that may serve as a helpful unifying framework for policy decisions on this topic. The primary audience for this Perspective is policymakers throughout the U.S. government who are working on quantum technology issues, but the material may also be of interest to officials in allied and partner nations, scientific researchers, or industry workers with stakes in U.S. policy decisions in this area.

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