QUANTUM TECHNOLOGY: A PRIMER ON NATIONAL SECURITY AND POLICY IMPLICATIONS

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Executive Summary

Quantum technologies are gaining prominence in policymaker dialogue yet remain a daunting topic for non-technical practitioners. "Quantum technologies" is a term used to define technologies that apply quantum phenomena to achieve some type of performance advantage. Major quantum technology areas that have become focal points for policymakers include quantum computing, quantum communication, and quantum sensing. While policymakers are aware that there may be national security-relevant applications of these technologies, most have only had limited engagement on the issue. One key barrier to more robust engagement is the gap between available technical literature and non-technical literature. This primer surveys the major aspects of quantum technologies that have been highlighted as having national security implications. The primer then provides technical background and reference materials on these topics and defines key terms. The goal of the primer is to provide policymakers and non-technical practitioners with a working knowledge of policy-relevant aspects of quantum technologies, which will be important for improved understanding of major obstacles to development and likely limitations upon eventual realization of quantum capabilities.

[1] *The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.*

Introduction

"Quantum technologies" is a term that broadly encompasses any type of technology that employs manipulation of quantum phenomena in its operation. Currently, there are three main branches of quantum technology: quantum sensing/metrology, quantum communication, and quantum computing. Across the three branches, these technologies leverage fundamental quantum principles, such as manipulable two-state quantum system dynamics, superposition, or entanglement.[2] The goal of harnessing these principles is to acquire a capability or operability improvement over a non-quantum alternative, or to enable an entirely new capability. Generally, these enhancements include increased speed of operation, improved sensitivity and accuracy of performance, bolstered security, or greater mobility and durability in adverse environments.

Within the past five years, government stakeholders have become increasingly aware of the potentially broad scope of impact for quantum technologies. The United States Congress passed the National Quantum Initiative Act (H.R.6227) in 2018, launching a "coordinated federal program" with the purpose of accelerating quantum technology development and application.[3] In addition to H.R.6227, the Executive Office National Science and Technology Council released a National Strategic Overview for Quantum Information Science that same year.[4] The Strategic Overview specifies the importance of an organized, government-wide approach in recognizing and responding to potential economic and national security implications of quantum technology development. Most recently, these efforts have been codified by a series of Executive Office memos released in 2022 highlighting post-quantum encryption capabilities and U.S. leadership as national security imperatives.[5] Furthermore, as researchers and analysts continue to assess efforts to upkeep the defense enterprise in a modern threat environment, quantum technologies are frequently included among lists of potentially impactful emerging technologies that merit deeper analysis and understanding.[6]

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[2] "Science and Tech Spotlight: Quantum Technologies," United States Government Accountability Office – Science, Technology Assessment, and Analytics, May 2020, from https://www.gao.gov/assets/gao-20-527sp.pdf.

[3] "National Quantum Initiative Act," United States 115th Congress, H.R. 6227, from https://www.congress.gov/bill/115th-congress/house-bill/6227/text.

[4] "National Strategic overview for Quantum Information Science," A Product of the Subcommittee on Quantum Information Science under the Committee on Science of the National Science and Technology Council – Untied States Executive Office, 2018, from https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf.

[5] "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems," The United States White House, May 4, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/04/national-security-memorandum-on-promoting-united-states-leadership-in-quantum-computing-while-mitigating-risks-to-vulnerable-cryptographic-systems/.

[6] For example: Jacek Durkalec, Anna Peczeli, and Brian Radzinsky, "Nuclear decision-making, complexity, and emerging disruptive technologies: A Comprehensive Assessment," European Leadership Network Report, February 14, 2022, https://www.europeanleadershipnetwork.org/report/nuclear-decision-making-complexity-and-emerging-and-disruptive-technologies-a-comprehensive-assessment/.

However, at the same time as policymakers and analysts are trying to get ahead of potential economic and national security risks, there is a core challenge in discussing topics of significant technical complexity in non-technical settings. Across the literature in the quantum technology field, there is a gap in the connection between technical literature discussing key R&D efforts and policy literature attempting to identify relevant applications. This gap has led to confusion over the likely scope of impact that quantum technologies may have and realistic timelines until significant disruptions are feasible.

This primer will help to alleviate the gap by surveying major policy-relevant areas and providing working definitions and technical context. The goal of the primer is to provide a baseline knowledge on quantum technologies as they relate to national security and policy applications, and to point readers towards relevant technical material. First, the primer will summarize emerging narratives on national security implications for quantum technologies. Next, the primer will define the different types of quantum technologies and platforms, as well as major use cases and R&D challenges. Finally, the primer will review current national policies governing quantum technology development, and provide recommendations based on the review of technical considerations.

Emerging Narratives on National Security Implications

Various defense enterprise stakeholders have commented on potential national security implications for quantum technologies. On national security impacts, analyses touch upon effects to economic security, intelligence acquisition, and physical defense and security assets. As with other emerging technologies, development in comparison to other countries is important; quantum technologies may pose risks if deployed by adversaries, while they may afford additional capabilities when deployed by the United States. Thus, an overarching trend of many of the analyses is determining the state of the art in quantum research and development, with a goal of identifying countries leading innovation.[7]

Feeding into national security concerns, mainstream media outlets have identified quantum technologies as a pillar for international technological competition. Typically, these articles resurface as various R&D milestones are achieved by either the United States or China to suggest that one country may be overtaking the other. For example, many speculated that

And: "Protecting Critical and Emerging U.S. Technologies from Foreign Threats," from The National Counterintelligence and Security Center, October 2021, https://www.dni.gov/files/NCSC/documents/SafeguardingOurFuture/FINAL_NCSC_Emerging%20Technologies_Factsheet_10_22_2021.pdf.

[7] For example, this can lead to insinuation of a "quantum arms race", as in: Jeremy Hsu, "The Race to Develop the World's Best Quantum Tech.," *IEEE Spectrum – New,* January 9, 2019, https://spectrum.ieee.org/race-for-the-quantum-prize-rises-to-national-priority.

China's launch of its quantum-focused satellite, Micius, in 2013 signaled the country's leadership over America.[8] Similarly, recent successful demonstrations by two different quantum computing research groups in China elicited a new wave of articles claiming China may soon usurp American leadership.[9] As Garisto points out, a key flaw in this narrative is that it is very hard to actually compare qualitative differences between two countries' quantum capabilities given the breadth of technologies included in the category and the nascency of the field.[10] Regardless of the inability to neatly compare, the sheer volume of articles that reference a quantum technology competition indicates that this is a major source of apprehension for actors in the sphere.

Mainstream thinktanks such as Deloitte,[11] McKinsey,[12] and AEI[13] have published longer reports assessing likely impact areas for various quantum technologies that are aimed at introducing quantum topics to policymakers and private sector stakeholders. Generally, these reports lack technical depth and instead focus narrowly on potential use cases for targeted audiences. However, without technical depth, their use case analyses are unable to provide deeper insight into realistic timelines or R&D pathways. They also tend to echo one another and re-iterate major use case areas, such as decryption through quantum computing or detection using quantum radar. As this report will show, there is often greater nuance in the likelihood of such applications and the feasible scope of capability improvement. Furthermore, these analyses are not catered towards providing policymakers with the tools to ask questions about these important topics, or to explore their own potential use cases beyond those presented in the report.

Similar analyses have reverberated among policy practitioners. The Congressional Research Services (CRS) has developed a brief primer that highlights similar military applications as those discussed by think tanks and expands to survey major issues for Congress, including funding volume and threat level questions.[14] Beyond the CRS report, individual government agencies,

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8 Lee Billings, "China Shatters "Spooky Action at a Distance" Record, Preps for Quantum Internet," *Scientific American*, June 15, 2017, https://www.scientificamerican.com/article/china-shatters-ldquo-spooky-action-at-a-distance-rdquo-record-preps-for-quantum-internet/.

9 Charles Choi, "Two of the World's Biggest Quantum Computers Made in China," *IEEE Spectrum*, November 6, 2021, https://spectrum.ieee.org/quantum-computing-china.

10 Daniel Garisto, "China is Pulling Ahead in Global Quantum Race, New Study Suggests," *Scientific American*, July 15, 2021, https://www.aei.org/wp-content/uploads/2021/04/Quantum-Computing.-A-National-Security-Primer.pdf?x91208.

11 Scott Buccholz, Joe Mariani, and Adam Routh, "The realist's guide to quantum technology and national security," Deloitte Insights Report, February 6, 2020, https://www2.deloitte.com/us/en/insights/industry/public-sector/the-impact-of-quantum-technology-on-national-security.html.

12 Gaurav Batra, Martina Gschwendtner, Ivan Ostojic, Andrea Queirolo, Henning Soller, and Linda Wester, "Shaping the long race in quantum communication and sensing," McKinsey Report, December 21, 2021, https://www.mckinsey.com/industries/advanced-electronics/our-insights/shaping-the-long-race-in-quantum-communication-and-quantum-sensing.

13 Klon Kitchen and Bill Drexel, "Quantum Computing: A National Security Primer," American Enterprise Institute, April 2021, https://www.aei.org/wp-content/uploads/2021/04/Quantum-Computing.-A-National-Security-Primer.pdf?x91208.

14 Kelley Sayler, "Defense Primer: Quantum Technology," Congressional Research Services, updated May 6, 2022, https://crsreports.congress.gov/product/pdf/IF/IF11836.

such as the Department of Homeland Security,[15] have recently issued basic plans for preparing for the advent and implementation of quantum technologies. At the international level, other countries are developing their own reference materials on quantum technologies[16] and even multilateral entities, such as NATO, are developing surveys and strategies to organize participants around key concepts.[17]

Among scientists, analyses are largely restricted to summaries of research results and technology review publications. One particularly relevant and groundbreaking analysis surveys specific military applications, though is limited in its discussion of broader strategic implications and particular use case analyses, as well as direct implications for policymakers.[18] For the most part, other scientists are focused on describing the evolution of research and development in specific technology areas[19] or presenting finding from their own research groups,[20] but largely ignore implications or discussion of relevant applications. Additionally, because these reports are narrowly focused on experimental findings, they often are myopic in the broader scope of quantum technology development.

Thus, although the current literature has served to raise the issues and potential implications for the emergence of quantum technologies, there is still work to be done to develop a working knowledge among practitioners on the technologies. A better understanding of how the technologies work, both at the basic level, as well as likely obstacles to achievement and parameters of feasible development, could provide policymakers with a better basis from which to assess policy proposals for the development of quantum technologies. The following section will survey the three branches of quantum technologies, and the types of platforms being developed in each. The section will also identify major use cases and obstacles, referencing relevant scientific articles to provide policymakers with a better technical perspective. Finally, better benchmarks for understanding capability levels will be discussed. This section will then lead to a reassessment of the current policies and governance strategies for quantum technologies, and recommendations for better policy implementation.

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15 "Final Report: Emerging Technologies Subcommittee Quantum Information Science," Department of Homeland Security Advisory Council, November 2020, https://www.dhs.gov/sites/default/files/publications/final_emerging_technologies_quantom_report_1.pdf.

16 For example: "Army Quantum Technology Roadmap," Australian Government Army, 2021, https://researchcentre.army.gov.au/sites/default/files/RD5734_Quantum%20Roadmap%20WEB.pdf.

17 Michiel van Amerongen, "Quantum technologies in defence and security," NATO Review, June 3, 2021, https://www.nato.int/docu/review/articles/2021/06/03/quantum-technologies-in-defence-security/index.html.

18 Michal Krelina, "Quantum technology for military applications," *EPJ Quantum Technology*, Vol 8, No. 4, 2021, https://epjquantumtechnology.springeropen.com/track/pdf/10.1140/epjqt/s40507-021-00113-y.pdf.

19 For example: C. Degen, F. Reinhard, and P. Cappellaro, "Quantum sensing," *Review of Modern Physics*, Vol 89, No. 035002, July 25, 2017, https://journals-aps-org.proxy-um.researchport.umd.edu/rmp/abstract/10.1103/RevModPhys.89.035002.
Or: Christopher Richardson, Vincenzo Lordi, Shashank Misra, and Javad Shabani, "Materials science for quantum information science and technology," MRS Bulletin, 2020.

20 For example, in a recent article neutral atom R&D conducted by a group was presented: Bluvstein, D., et. al., "A quantum processor based on coherent transport of entangled atoms," *Nature*, 604, 2022, https://www.nature.com/articles/s41586-022-04592-6.

Quantum Technology Primer

One of the key barriers to better understanding the quantum technology field is the sheer variety in the types of technologies and platforms involved. This section will provide an overview of the major quantum technology categories, including technical characteristics, types of platforms under development, defense-relevant use cases, and major R&D obstacles. Although this section will only provide the basic introduction to these topics, technical references will be provided to point readers to further reference materials. Appendices are also used to provide deeper-level knowledge that may not necessarily be as pertinent, but that may allow for better understanding on the technical dimensions of these systems.

There are three main branches of quantum technology: quantum computing, quantum communication, and quantum sensing. All three branches leverage quantum phenomena, including quantum entanglement, quantum superposition, and quantum tunnelling, which are described in greater detail in Appendix A. These technologies comprise what is often referenced as the "second quantum revolution."[21] This means that, in addition to leveraging many quantum systems at the aggregate level, such as is customary in the semiconductor industry, these technologies also rely on the ability to manipulate individual quantum systems, or "qubits" (a term used to describe the elementary unit of quantum information).[22]

Major Use Cases Driving Interest Across Quantum Technologies

As interest in quantum technology escalates, potential use cases for each branch of quantum technology are also being considered in by the private and defense spheres. Evidenced by increased funding volumes, private sector optimism for eventual quantum application is surging, largely in part due to the variety of use cases that have emerged.[23] In quantum computing, proposed private sector use cases include financial analysis,[24] biophysics simulations, complex manufacturing, and basic research.[25] For quantum communication, private sector interest revolves around improved networking for banking and business cyber security.[26] And in quantum sensing, private sector interest includes improved energy and land surveying

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21 Jonathan Dowling and Gerard Milburn, "Quantum Technology: The Second Quantum Revolution," *Philosophical Transactions of the Royal Society of London*, Series A: Mathematical, Physical and Engineering Sciences, vol. 361, no. 1809, 2003.

22 Ibid, pp. 1663.

23 Elizabeth Gibney, "Quantum gold rush: the private funding pouring into quantum start-ups," *Nature*, October 2, 2019.

24 Miklos Dietz, Nico Henke, Jared Moon, Jens Backes, Lorenzo Pautasso, and Zaheen Sadeque, "How quantum computing could challenge financial services," MicKinsey, December 18, 2020, https://www.mckinsey.com/industries/financial-services/our-insights/how-quantum-computing-could-change-financial-services.

25 Francesco Bova, Avi Goldfarb, and Roger Melko, "Quantum Computing is Coming. What Can it Do?," Harvard Business Review – Innovation, July 16, 2021, https://hbr.org/2021/07/quantum-computing-is-coming-what-can-it-do.

26 Gibney, 2019

capabilities,[27] medical imaging, and automation, among others.[28] Although separate from defense interests, maintaining private sector interest and funding may be critical in sustaining R&D momentum and retaining human talent.[29]

As discussed earlier, in addition to private sector interest, quantum technologies have also garnered governmental attention due to use cases relevant to national security and defense activities. As presented in Figure 1, the main use cases for quantum computing revolve around data processing capabilities, such as for large data analysis, optimization of higher-dimensional problems, and potentially cracking modern encryption standards (a capability predicted by Shor's algorithm[30]). For quantum communication, increased security and connectivity in information transfer is the major use case. And for quantum sensing, a variety of more narrowly applicable use cases have emerged that allow for improved accuracy for navigation or better imaging for detection. Each of these aspects of the different branches will be discussed in greater detail in the subsequent section. However, it is worth noting that as quantum technologies reach a more advanced stage of development, and their capabilities become better understood, it is possible that entirely new use cases will be identified.

Figure 1 also provides rough estimates for timelines until these capabilities are achieved, although there is notable disagreement among experts over these timelines. Specifically, significant disagreement derives from speculation over the feasibility of sustained, long-term R&D interest and resource allocation. As the National Academies report on quantum computing points out, many estimates inherently rely on the assumption of a "virtuous cycle of progress" where near-term applications and breakthroughs enable down-stream development.[31] Because of this assumption, some estimates could be overzealous. For example, scenarios where quantum technologies fail to succeed in meeting near-term expectations could result in lower funding, which would impede R&D progress (a scenario referred to as a "quantum winter").[32]

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[27] Scott Crawford, Roman Shugayev, Hari Paudel, Ping Lu, Madhava Syamlal, Paul Ohodnicki, Benjamin Chorpening, Randall Gentry, and Yuhua Duan, "Quantum Sensing for Energy Applications: Review and Perspective," *Advanced Quantum Technologies*, Vol. 4, No. 8, 2021, https://onlinelibrary.wiley.com/doi/full/10.1002/qute.202100049.

[28] "Bringing Quantum Sensors to Fruition," A Report by the Subcommittee on Quantum Information Science Committee on Science of the U.S. National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

[29] Mateusz Masiowski, Niko Mohr, Henning Soller, and Matija Zesko, "Quantum computing funding remains strong, but talent gap raises concern," McKinsey Digital, June 15, 2022, https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/quantum-computing-funding-remains-strong-but-talent-gap-raises-concern.

[30] Thomas Monz, Daniel Nigg, Esteban Martinez, Matthias Brandl, Philipp Schindler, Richard Rines, Shannon Wang, Isaac Chuang, and Rainer Blatt, "Realization of a scalable Shor algorithm," *Science,* Vol. 351, No. 6277, 2016, https://www-science-org.proxy-um.researchport.umd.edu/doi/abs/10.1126/science.aad9480.

[31] "Feasibility and Time Frames of Quantum Computing," Chapter 7 in *Quantum Computing: Progress and Prospects*, 2019, Pp. 158-159, https://nap.nationalacademies.org/read/25196/chapter/9#158.

[32] Michael Brooks, "Beyond quantum supremacy: the hunt for useful quantum computing," *Nature*, October 2019, https://www.nature.com/articles/d41586-019-02936-3.

Figure 1: Major National Security-Relevant Use Cases and Projected Timelines[33]

Quantum Technology	Quantum Computing	Quantum Communication	Quantum Sensing
Top National Security Implications	• Decryption (via Shor's algorithm) • Large data analysis • System optimization processes	• Secure communication • Improved connectivity	• Subsurface detection • Positioning, navigation, and timing (PNT) • Timekeeping for precise operations • Verification • Radar and imaging
Projected Timeline	• Minimal cloud access currently available (mostly for simulations) • NISQ (single-use, limited capability) – 5-10 years • Important applications and general use - >20 years	• Limited capabilities already commercially available • In the next 10-15 years will likely see some early forms of networking	• Some sensors are commercially available • In the next 10 years, will likely see more rugged/mobile products • In the next 20+ years could see radar/entanglement-based systems

Use Cases and Technical Background by Quantum Technology Category

1. Quantum Computing

Quantum computing is perhaps the best known of the three quantum technology categories and has received the greatest level of media interest. As will be detailed below, the physics of quantum computers allows them to perform more complex calculations and at faster speeds than non-quantum alternatives. The major issues discussed in the context of quantum computing development include rapid, large-scale data analysis, complex systems optimization, and improved data decryption capabilities.[34] Security-relevant use cases in these areas include:

- **Large data analysis**: Quantum computers could yield a tremendous intelligence, surveillance, and reconnaissance (ISR) advantage through allowing for more rapid large-scale data analysis or evaluation of more complex systems. In recent years, ISR assets, and related data processing modernization efforts, have been highlighted as a pivotal

[33] Figure information references:
Edward Parker, Daniel Gonzaels, Ajay Kochhar, Sydney Litterer, Kathryn O'Connor, Jon Schmid, Keller Scholl, Richard Silberglitt, Joan Chang, Christopher Eusebi, and Scott Harold, "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," RAND Research Report, 2022, https://www.rand.org/pubs/research_reports/RRA869-1.html.
Edward Parker, "Commercial and Military Applications and Timelines for Quantum Technology," RAND Research Report, 2021, https://www.rand.org/pubs/research_reports/RRA1482-4.html.
"Bringing Quantum Sensors to Fruition," A Report by the Subcommittee on Quantum Information Science Committee on Science of the U.S. National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.
Krelina, 2021.
Michael Biercuk and Richard Fontaine, "The Leap into Quantum Technology: A Primer for National Security Professionals," *War on the Rocks*, 2017, https://warontherocks.com/2017/11/leap-quantum-technology-primer-national-security-professionals/.

[34] For example, outlined in: Scott Buccholz, Joe Mariani, and Adam Routh, "The realist's guide to quantum technology and national security," Deloitte Insights Report, February 6, 2020, https://www2.deloitte.com/us/en/insights/industry/public-sector/the-impact-of-quantum-technology-on-national-security.html.

requisite in the strategy to uphold security against Russia and China.[35] Specifically, it has been suggested that the ability to analyze available ISR data swiftly to identify patterns or to detect signals may yield a critical time advantage over an adversary or help reduce the "fog of war" through providing time-sensitive information.

- **Complex systems optimization**: Similarly, the ability to tackle larger data sets with higher degrees of complexity is advantageous for many logistics or complex system optimization tasks. Systems agility is important as these activities become more contested, with adversaries seeking to disrupt U.S. supply chains and military logistics planning and as decreased response time becomes a higher strategic priority.[36] Additionally, quantum computers could be used to reinforce military artificial intelligence or machine learning systems.[37]

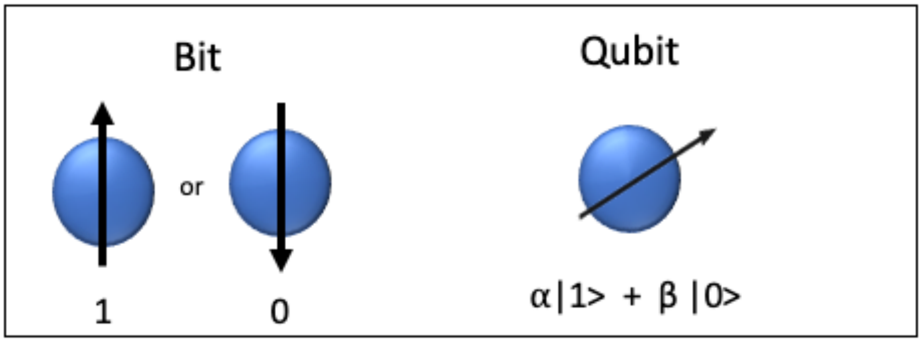
- **Data decryption**: Finally, and most notably, quantum computers could have the potential to crack modern data encryption methods. This has been highlighted by the Biden Administration as one of the most significant impacts of quantum technology, and a critical national security concern.[38] This means that an adversary in possession of a quantum processor could theoretically decrypt sensitive information that has been encrypted using modern protocols. Although, there has been some disagreement over the size and power a quantum computer would need to perform such decryption, and use of post-quantum encryption methods may eventually serve as an effective countermeasure.[39]

But how do quantum computers achieve these improvements? In quantum computers, qubits are somewhat analogous to bits in a classical computer. However, while bits are binary, and thus are either in 0 or 1 positions, qubits can leverage the superposition quantum phenomenon to exist in some combination of both 0 and 1 simultaneously, depicted in Figure 2.[40] This means, that while a two-bit system can be in one of four states (00, 01, 10, 11), a two-qubit system can be in all four simultaneously. Thus, as the number of qubits in a system increases, the increased

[35] Nishawn Smagh, "Intelligence, Reconnaissance, and Surveillance Design for Great Power Competition," Congressional Research Service, June 4, 2020, https://sgp.fas.org/crs/intel/R46389.pdf.
[36] John Polowczyk, Robert Lytle, Frank Futcher, "Four actions to modernize military logistics and supply chain security," Ernst and Young, March 25, 2022, https://www.ey.com/en_us/strategy/four-actions-to-modernize-military-logistics-and-supply-chain-security.
[37] Max Levy, "Machine Learning Gets a Quantum Speedup," Quanta Magazine, February 4, 2022, https://www.quantamagazine.org/ai-gets-a-quantum-computing-speedup-20220204/.
[38] "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Risks to Vulnerable Cryptographic Systems," United States Executive Office, May 4, 2022.
[39] Davide Castelvecchi, "The race to save the internet from quantum hackers," *Nature*, February 8, 2022, https://www.nature.com/articles/d41586-022-00339-5.
[40] Eleanor Rieffel and Wolfgang Puck, "An Introduction to Quantum Computing for Non-Physicists," *ACM Computing Surveys*, Vol. 32, No. 3, September 2000, pp. 300-335.

processing capacity of a quantum register (or a string of qubits) theoretically increases by 2^n for n qubits in the register.[41] (However, the extent to which this full performance increase is achieved depends on the type of quantum processor and the fidelity and connectivity of the qubits, which will be discussed in a later section).

Figure 2: State of Classical Bit versus a Quantum Qubit



Note: A bit can either be in a one or zero state, but a qubit can be in a superposition of both states. This superposition state is denoted in Dirac/"bra-ket"[42] notation to indicate the probabilistic nature.

Thus, through quantum mechanics, quantum computers have the potential to outperform classical computers in both speed and complexity. On one hand, because they can be in 2^n states for n qubits, when compared to classical computers, they may be able to operate at exponentially faster speeds than classical computers.[43] However, additionally, because different types of gates and operations are used to perform calculations compared to traditional computers and because connectivity and entanglement between qubits can be achieved, quantum computers may be able to handle more complex tasks.[44] Although, as preeminent quantum computing scholar John Preskill notes, it is hard to even comprehend the ways in which quantum computers will compare to classical computers, given that we are still at such an early stage of development.[45]

Despite major theoretical and experimental advances, operable quantum computers have been difficult to achieve practically. In order for quantum computers to fully leverage quantum

[41] Rieffel and Puck, pp. 302.

[42] E. Knill, R. Laflamme, H. Barnum, D. Dalvit, J. Dziarmaga, J. Gubernatis, L. Gurvitis, G. Ortiz, L. Viola, and W. H. Zurek, "Introduction to Quantum Information Processing," February 1, 2008, pp. 5, https://arxiv.org/pdf/quant-ph/0207171.pdf.

[43] Rieffel and Puck, pp. 303.

[44] Norbert Linke, Dmitri Maslof, Martin Roetteler, Shantanu Debnath, Caroline Figgat, Kevin Landsman, Kenneth Wright, and Christopher Monroe, "Experimental comparison of two quantum computing architectures," *Proceedings of the National Academy of Sciences*, Vol. 114, No. 13, 2017, https://www-pnas-org.proxy-um.researchport.umd.edu/doi/abs/10.1073/pnas.1618020114.
And: Adam Holmes, Sonika Johri, Gian Gurreschi, James Clarke, and Matsuura, "Impact of qubit connectivity on quantum algorithm performance," *Quantum Science and Technology*, Vol. 5, No. 025009, https://iopscience.iop.org/article/10.1088/2058-9565/ab73e0.

[45] John Preskill, "Quantum Computing in the NISQ era and beyond," *Quantum*, arxiv:1801.00862, 2018, https://quantum-journal.org/papers/q-2018-08-06-79/pdf/.

advantages, they must be well protected from environmental perturbations, such as instrumental signals or ambient electric and magnetic fields.[46] Once perturbations impact the quantum system, the superposition state undergoes decoherence, which means that the qubit alignment (and functionality) degrades. As will be discussed in a later section, techniques to improve protection methods for quantum computers and to shield them from environmental disturbances OR to incorporate error correction to account for small amounts of decoherence have become major research areas in quantum technology development.[47]

However, in the meantime these roadblocks mean that useful quantum computers are still not likely in the near term (less than 10 years). Instead, the field is likely to see the attempt to use "noisy, intermediate scale quantum computers" (or NISQ computers) in the near to medium term (over the next 10-20 years).[48] And although NISQ computers will have some advantage over conventional computers, they are unlikely to truly enable the capability improvements needed for the major applications identified above. However, despite the longer realistic time horizon than is often assumed, the uncertainty over a true timeline to more operable quantum computing makes preparation and flexibility a requirement.[49]

2. Quantum Communication

Quantum communication also relies on qubits, but instead leverages the sensitivity of the quantum systems to ensure secure transfer of information. In comparison to quantum computing, the national security implications for quantum communication systems are narrower. Secure and potentially more rapid communication capabilities could allow for increased security of data transmission. Conversely, if adversaries can achieve quantum communication capabilities, it is possible that U.S. ISR data acquisition would be negatively impacted. However, a significant amount of skepticism has been raised over the true benefits gained through implementing quantum communication techniques, given that secure communication technology alone may not completely prevent the hacking of data transmission or leaking of secure information (for example, social mechanisms could also lead to these consequences, regardless of the technologies at hand).[50]

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[46] Scott Aaronson, "What makes quantum computing so hard to explain?" *Quanta Magazine*, June 8, 2021.

[47] Joscha Roffe, "Quantum error correction: An introductory guide," *Contemporary Physics*, Vol. 60, No. 3, 2019.

[48] John Preskill, "Quantum computing in the NISQ era and beyond," *Quantum*, No. 2, pp. 79, 2018, https://quantum-journal.org/papers/q-2018-08-06-79/.

[49] "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Risks to Vulnerable Cryptographic Systems," United States Executive Office, May 4, 2022.

[50] Edward Parker, "Commercial and Military Applications and Timelines for Quantum Technology," RAND Research Report, 2021, https://www.rand.org/pubs/research_reports/RRA1482-4.html.

One of the most paramount features of quantum systems (and most notorious, by virtue of Schrodinger's cat) is that when they are measured, their superposition state collapses.[51] Thus, if qubits are used to encode decryption keys or information, by virtue of the measurement theory, eavesdropping or hacking should be evident.[52] Beyond this premise, there are a few different methods to operationalize quantum communication; the information or key could simply be encoded on a qubit, or entanglement or teleportation phenomena of quantum systems could also be exploited to transfer information at extremely fast speeds.[53]

Quantum key distribution (QKD) is the main form of quantum communication that has been the focus of research thus far. In a sense, QKD is similar to standard key-based encryption systems, where encoded information is shared between two parties with a secure key that can be used to decrypt the message. However, a long-standing problem has been ensuring that keys remain private from eavesdroppers, with added assumptions about how much time factoring a long string of numbers without a key would take.[54] In QKD, quantum mechanics allows inherent security of the key. Because of the quantum non-cloning theorem, eavesdroppers are physically unable to intercept and copy the key during transmission.[55] Additionally, any attempt to intercept the message would be detectable by the communicating parties.[56]

On a small scale, QKD is feasible with current technologies and has already been demonstrated, yet there are likely to be challenges in expanding the scope of quantum communication capabilities. Like quantum computing, quantum communication methods are also prone to environmental perturbations, especially as the distance of the communication transit increases. New hardware and error correction techniques are likely to be needed to continue to increase the distance of transmission.[57] One approach that is currently being used to circumvent existing constraints is satellite-based QKD. In this method, satellites serve as intermediary nodes to enable communication across further distances without overextending the limits of current quantum communication technologies.[58] Additionally, many practitioners have suggested that quantum communication can be used at an even larger, more distributed scale to establish a

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[51] C. Monroe, "Quantum information processing with atoms and photons," *Nature*, Vol. 416, March 14, 2002.
[52] Ibid.
[53] Nicolas Gisin and Rob Thew, "Quantum Communication," *Nature Photonics*, Vol. 1, No. 3, 2007.
[54] Eleni Diamanti, Hoi-Kwong, Bing Qi, and Zhiliang Yuan, "Practical Challenges in Quantum Key Distribution," *Nature – Quantum Information*, 2016, no. 16025.
[55] Diamanti, Hoi-Kwong, Qi, and Yuan, 2016.
[56] Omar Amer, Vaibhav Garg, Walter Krawec, "An Introduction to Practical Quantum Key Distribution," *IEEE Aerospace and Electronic Systems Magazine*, March 1, 2021, https://www.semanticscholar.org/paper/An-Introduction-to-Practical-Quantum-Key-Amer-Garg/936141dc48112bbe96070540873eef6790fb4b35.
[57] Diamanti, Hoi-Kwong, Qi, and Yuan, 2016.
[58] Robert Bedington, Juan Arrazola, and Alexander Ling, "Progress in satellite quantum key distribution," *Nature Quantum Information*, Vol. 3, No. 30, 2017.

quantum communication network (or even a quantum internet).[59] However, this would require increased linkage of nodes and improved quantum entanglement and quantum memory techniques and hardware, and thus is likely not feasible in the near to medium term.[60]

3. Quantum Sensing

Quantum sensors comprise the third and final branch of quantum technologies, and leverage quantum phenomena to measure physical properties. The major security implications pertain to the ability of quantum sensors to improve sensitivity in analyzing magnetic fields, electric fields, gravitational fields, or other physical properties, as well as the fact that they may be able to operate in more adverse conditions than non-quantum alternatives. Relevant use cases arising from these capabilities include:

- **Navigation:** Quantum sensors enable improved accuracy of navigation through increased sensitivity of positioning measurements compared to non-quantum alternatives. This enhancement can be useful for maneuvering fast-moving autonomous systems or for improving missile accuracy, among other operations that require ultra-precise positioning. However, additionally, quantum sensors may benefit from improved operability in adverse conditions. Because quantum sensors rely on magnetic fields, gravitational fields, or acceleration to determine positioning and to navigate, they are able to operate for some duration of time without external signals from a GPS or satellite/communication system (a capability referred to as "dead-reckoning").[61] Thus, a major advantages of quantum sensor-based navigation is that it can be used in areas where GPS signal is lacking, such as in space or underwater, and additionally it is less susceptible to spoofing or other forms of interference.[62]

- **Timekeeping:** The quantum sensor category also includes quantum timekeeping devices, which can allow for faster communication, improved connectivity with satellites, and more rapid data transmission.[63] These benefits are becoming more important as the demand for faster paced operations increases. They also may eventually enable improved performance of automated systems and better

59 Christoph Simon, "Towards a global quantum network," *Nature Photonics*, Vol. 11, November 2017.
60 Khabat Heshami, Duncan England, Peter Humphreys, Philip Bustard, Victor Acosta, Joshua Nunn, and Benjamin Sussman, "Quantum memories: emerging applications and recent advances," *Journal of Modern Optics*, vol. 63, No. 20, 2016.
61 Donghui Feng, "Review of Quantum Navigation," *IOP Conference Series: Earth and Environmental Science*, Vol. 237, No. 032027, 2019, https://iopscience.iop.org/article/10.1088/1755-1315/237/3/032027/pdf.
62 Parker, 2021.
63 Parker, 2021.

synchronization of networked systems, such as drone swarms[64] and satellite constellations,[65] but limited testing has been done to verify these claims to-date.

- **Signal detection:** Quantum sensors allow for better signal detection through increased sensitivity over non-quantum alternatives, permitting detection even when there is a lower signal-to-noise ratio for the target signal. Use cases for signal detection include communication interception through radiofrequency analysis or subsurface detection, such as for submarine tracking[66] or tunnel monitoring,[67] through gravity field or magnetic field interrogation.[68] Additionally, quantum sensors may be more beneficial for long-term or mobile surveillance and detection operations, as they are expected to have improved size, weight, and performance characteristics at lower costs (SWAP-C), meaning they are smaller and lighter, and thus more mobile.[69] (C-SWAP parameter improvements will likely be advantageous for the other quantum sensor applications as well)

Given that quantum sensing is the most developed of the three categories, greater clarity has emerged on the specific use cases than for other quantum technologies.[70] Figure 3, below, breaks out the broader set of uses cases based on the types of physical properties that quantum sensor systems measure. Quantum sensing has drawn some private sector interest, but is largely being supported by government and military stakeholders. As Figure 3 indicates, use cases relevant to defense and national security activities have been identified across each of the different types of platforms. Figure 3 also shows the ways in which sensors measuring different properties may still be used for the same application, such as how magnetic field navigation and gravitational field navigation may both be used for positioning, navigation, and timekeeping improvements, which is another source of confusion in the field. Finally, it should be noted that the applications detailed in Figure 3 are non-comprehensive, and more applications are likely to emerge as the field progresses.

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64 Adarsh Kumar, Diego Augusto de Jesus Pacheco, Keshav Kaushik, and Joel J.P.C. Rodrigues, "Futuristic view of the Internet of Quantum Drones: Review, challenges, and research agenda," *Vehicular Communications*, Vol. 34, 2022, https://www.sciencedirect.com/science/article/pii/S2214209622000341.

65 Haosheng Zhang, Hans Herdian, Aravind Tharayil Narayanan, Atsushi Shirane, Mitsuru Suzuki, Kazuhiro Harasaka, Kazuhiko Adachi, Shinya Yanagimachi, Kenichi Okada, "Ultra-Low-Power Atomic Clock for Satellite Constellation with 2.2x10^-12 Long-Term Allan Deviation Using Cesium Coherent Population Trapping," *IEEE International Solid-State Circuits Conference*, February 2019, https://ieeexplore.ieee.org/document/8662498.

66 Marco Lanzagorta, Jeffrey Uhlmann, and Salvador Venegas-Andraca, "Quantum Sensing in the Maritime Environment," *IEEE Washington*, 2015, https://ieeexplore.ieee.org/document/7401973.

67 Nicola Poli, Roman Pasteka, and Pavol Zahorec, "Atomic changes can map subterranean structures," *Nature*, February 23, 2022, https://pubmed.ncbi.nlm.nih.gov/35197614/.

68 Parker, 2021.

69 "Applications of Quantum Technologies," Office of the Undersecretary of Defense for Research and Engineering, October 2019, https://www.globalsecurity.org/military/library/report/2019/quantum-technologies_execsum_dsb_20191023.pdf.

70 Chris Hoofnagle and Simon Garfinkle, "Quantum Sensors – Unlike Quantum Computers – Are Already Here," *Defense One*, June 27, 2022, https://www.defenseone.com/ideas/2022/06/quantum-sensorsunlike-quantum-computersare-already-here/368634/.

Figure 3: Quantum Sensor Use Cases and Relevant Industries, by Type of Signal Measured[71]

Property measured	Gravitational field/gradient	Inertia/ acceleration	Electric field	Magnetic field	Spectroscopy/ photon	Time
Use case activities	• Navigation • Sub-surface detection	• Navigation • Positioning	• Condition monitoring • RF detection • Remote sensing	• Trace detection • MRI • Surveying • Metal and subsurface detection • Navigation	• Diagnostic imaging • Leak detection • Radar • Remote sensing	• Time distribution • Surveying • Navigation
Relevant industries	• Defense and security • Energy and mining • Environmental monitoring	• Defense and security • Automation • Transportation	• Industry • Defense and security • Automation • Transportation	• Industry • Medical • Energy and mining • Construction • Defense and security	• Industry • Medical • Energy and mining • Construction • Defense and security • Automation	• Industry • Construction • Defense and security • Finance • Automation

While environmental perturbations are impediments in quantum communication and quantum computing, they are operationalized in quantum sensing. Instead of avoiding systems that are sensitive to these factors, quantum sensors seek to quantify environmental properties, such as electric and magnetic field strength, gravitational field strength, time, and acceleration. With this aptitude, quantum sensors can be used for a variety of activities, from medical and environmental imaging to subsurface detection and positioning, navigation, and timing.

The process for measuring different properties varies depending on the platform/qubit used for a specific sensor. As will be discussed in a later section, a variety of platforms may be used as quantum sensors, including neutral atoms, photons, defects in diamonds, and superconducting circuits.[72] In each of these platforms, the initial state of the qubit must be able to be measured, the qubit must have some known response pattern to the property measured, and the qubit must be able to be measured after some known period of time during which it is exposed to the environmental perturbation.[73] Interestingly, some forms of quantum sensors have been around

[71] Edward Parker, "Commercial and Military Applications and Timelines for Quantum Technology," RAND Research Report, 2021, https://www.rand.org/pubs/research_reports/RRA1482-4.html.
"Bringing Quantum Sensors to Fruition," A Report by the Subcommittee on Quantum Information Science Committee on Science of the U.S. National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.
Degen, Reinhard, and Cappellaro, 2017.

[72] Degen, Reinhard, and Cappellaro, 2017.

[73] Degen, Reinhard, and Cappellaro, 2017.

for decades, such as the superconducting quantum interference device (SQUID), which is used to measure magnetic fields.[74] However, the second quantum revolution has introduced the power to better control individual quantum systems, rather than treat them in aggregate, allowing for increased operability and, in some cases, improved C-SWAP parameters.[75]

While quantum sensing is at the most advanced stage of development of the three quantum technology areas, there are still limits to its operability. On the experimental side, more research is needed to characterize the performance of these systems in different settings and applications, which will be an essential steppingstone towards eventual application.[76] Additionally, from the production side, greater analysis is needed to develop a more robust supplier base that will pave the way for sustainable acquisition of necessary materials and sub-technology components for quantum sensing systems before they can be commercialized.[77]

Interestingly, there is a significant overlap in the techniques and materials improvements needed for quantum sensing and the other two quantum technology areas discussed above. Noteworthy breakthroughs in any of these three fields is likely to also improve understanding in the other two. Thus, although the three fields are somewhat separate in terms of their applications and consumer bases, the underlying research and development and fabrication requirements are still linked, which means research gaps in overlapping areas should be treated as multiplicative in the magnitude of their impact.

Policy Approaches and National Strategies

As quantum technologies become more advanced and new potential use cases emerge, governments worldwide are racing to assert quantum development policies and national strategies to capture economic, technical, and strategic benefits from the technologies. Within the past 10 years, the United States has iteratively expanded the scope of its national quantum resourcing policies and strategic approach. At the same time, other countries are also adopting their own plans to keep pace with the international domain. Interestingly, different approaches that countries have taken in drafting quantum technology plans may shed light on the variety of methods governments use to fund technology development and their priorities in responding to technology competition. This section will survey the policies adopted thus far and will attempt to highlight the major themes in each countries' approach.

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[74] Evelyn Lamb, "The quantum squeeze," *Symmetry*, January 25, 2022, https://www.symmetrymagazine.org/article/the-quantum-squeeze.

[75] Degen, Reinhard, and Cappellaro, 2017.

[76] Degen, Reinhard, and Cappellaro, 2017.

[77] Scott Crawford, Roman Shugayev, Hari Paudel, Ping Lu, Madhava Syamlal, Paul Ohodnicki, Benjamin Chorpening, Randall Gentry, and Yuhua Duan, "Quantum Sensing for Energy Applications: Review and Perspective," *Advanced Quantum Technologies*, Vol 4, No. 2100049, 2021.

U.S. Quantum Policies and Strategy

The first unified government approach taken by the United States was the 2018 National Quantum Initiative Act (NQIA). The stated purpose of the NQIA was "to accelerate quantum research and development for the economic and national security of the United States." Subsequently, quantum programs were included in the National Defense Authorization Acts for 2019-2022, for the purpose of authorizing the Department of Defense to improve the national quantum technology readiness level and allocate necessary resources. Additionally, the government established "Quantum Leap Challenge Institutes" to serve as centralized hubs for quantum resources and to facilitate shared expertise and knowledge across multidisciplinary research groups.[78] Contemporaneously, the U.S. government continued to cultivate interagency infrastructure to relay findings and research across the government enterprise. Throughout the maturation of the national quantum response, this evolved from irregularly convening a small, somewhat interagency quantum task force[79] and an occasional congressional hearing,[80] into the establishment of a full-fledged, centralized quantum website (quantum.gov) to announce initiatives, resources, and research progress, as well as to connect stakeholders. Thus, the U.S. approach reflects a dynamic web weaved of top-down and bottom-up elements.

Already in 2022, the U.S. government has taken steps to expand its network and to codify its national strategy. Earlier this year, the government announced a sweeping series of strategic partnerships/cooperation agreements to formalize relationships with allies on strategic development, including with Sweden,[81] Finland,[82] and Denmark,[83] with more likely to follow and in addition to existing partnerships with Japan, Australia, and the United Kingdom[84]. The Executive Branch also published two memoranda in May 2022 on the imperative of U.S.

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78 "National Quantum Initiative Supplement to the President's FY 2022 Budget," A Report by the Subcommittee on quantum information science committee on science of the National Science and Technology Council, December 2021, https://www.quantum.gov/wp-content/uploads/2021/12/NQI-Annual-Report-FY2022.pdf.
And: Quantum Leap Challenge Institutes – Program Solicitation, NSF 19-559, https://www.nsf.gov/pubs/2019/nsf19559/nsf19559.pdf.

79 Steven Rich and Barton Gellman, "NSA Seeks to Build Quantum Computer That Could Crack Most Types of Encryption," *Washington Post*, January 2, 2014, https://www.washingtonpost.com/world/national-security/nsa-seeks-to-build-quantum-computer-that-could-crack-most-types-of-encryption/2014/01/02/8fff297e-7195-11e3-8def-a33011492df2_story.html.

80 "American Leadership in Quantum Technology," Joint Hearing Before the, Committee on Science, Space and Technology, 105th Congress, SN 115-32, October 24, 2017, https://www.govinfo.gov/content/pkg/CHRG-115hhrg27671/html/CHRG-115hhrg27671.htm.

81 "Joint Statement of the United States of America and Sweden on Cooperation in Quantum Information Science and Technology," U.S. Department of State, April 12, 2022, https://www.state.gov/joint-statement-of-the-united-states-of-america-and-sweden-on-cooperation-in-quantum-information-science-and-technology/.

82 "Joint Statement of the United States of America and Finland on Cooperation in Quantum Information Science and Technology," U.S. Department of State, April 6, 2022, https://www.state.gov/joint-statement-of-the-united-states-and-finland-on-cooperation-in-quantum-information-science-and-technology/.

83 Joint Statement of the United States of America and Denmark on Cooperation in Quantum Information Science and Technology," U.S. Department of State, June 7, 2022, https://www.state.gov/joint-statement-of-the-united-states-of-america-and-denmark-on-cooperation-in-quantum-information-science-and-technology/.

84 Alexandra Kelley, "The U.S. is keen to get ahead in the global quantum race as national security and technological innovation intersect," *Nextgov*, 2022, https://www.nextgov.com/emerging-tech/2022/04/more-international-quantum-partnerships-likely-us-stakes-claim-field/365664/.

quantum technology leadership and the necessity to prepare for national security challenges that may arise from post-quantum decryption capabilities.[85]

Global Quantum Policies and Strategies

Other countries are also racing to develop quantum technologies and establish governmental guardrails. As Table 1 shows, at least 13 countries, in addition to the United States, have developed national quantum technology initiatives. Of those 13, a majority were established within the past five years alone. This trend indicates that countries are vying to establish their own policies and to assert their position among the global technology scene, which makes it likely that many other countries will follow suit and develop policies in the next few years.

Additionally, Table 1 highlights that each strategy reflects a slightly different approach towards research and development governance. For example, some countries are competing for primacy in certain branches of quantum technologies. China and Japan have long staked their interest in quantum communication, while the United States and the United Kingdom are leading in quantum sensing development. Interestingly, Canada has a comparatively long history of investing in quantum computing. Apart from technology focus areas, countries are also generally funding and fostering R&D in different ways. For example, Russia and China have approached quantum R&D through extremely centralized efforts, including funneling resources to state-run universities and research centers, while the United States and Canada have leveraged strong private sector innovation hubs to catalyze quantum technology efforts.[86]

Depending on the governance strategy adopted, countries are likely to face different obstacles in developing robust quantum industries. Because the United States is relying more on its private sector to drive innovation, there is greater concern over "technology leakage" to other countries and potential scenarios that could impact private sector funding interest (as discussed earlier – "quantum winters").[87] Meanwhile, countries that primarily rely on centralized entities may notice difficulty in drawing and maintaining personnel talent, or else may find it difficult to achieve long-term economic viability without significant state-drawn resources.[88]

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[85] National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems," The United States White House, May 4, 2022.

[86] James Lewis, "Mapping the National Security Industrial Base: Policy Shaping Issues, May 19, 2021, CSIS Report, https://www.csis.org/analysis/mapping-national-security-industrial-base-policy-shaping-issues.

[87] Chris Hoofnagle and Simson Garfinkle, "What if Quantum Computing is a Bust?" *Slate*, Jan 26, 2022, https://slate.com/technology/2022/01/quantum-computing-winter-scenario.html.

[88] Edward Parker, Daniel Gonzaels, Ajay Kochhar, Sydney Litterer, Kathryn O'Connor, Jon Schmid, Keller Scholl, Richard Silberglitt, Joan Chang, Christopher Eusebi, and Scott Harold, "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology," RAND Research Report, 2022, https://www.rand.org/pubs/research_reports/RRA869-1.html.
And more generally: Regina Abrami, William Kirby, and Warren McFarlan, "Why China Can't Innovate," *Harvard Business Review*, March 2014, https://hbr.org/2014/03/why-china-cant-innovate.

Table 1: Summary of Global National Initiatives for Quantum Technology Development[89]

China	Have been featured in Made in China 2025 and Five Year Plan national strategies
	Centralized approach through national labs and universities; **leading in communication**
United Kingdom	Established in 2013
	Deep industry focus; **leading with U.S. in quantum sensing**
Germany	Established national strategy in 2018
	Emphasis on communication and industry-academia collaboration
Japan	Established in 2020
	Focused around 4 key application areas (i.e. AI and bio); **leading with China in communication**
Russia	Established in 2019
	Focused on three state-owned organizations
Canada	Established national strategy in 2016
	Emphasizes industry-academia consortia; **leading with U.S. in quantum computing**
Australia	Established 2021/2022 ("National Quantum Strategy")
	Organized around silicon-based quantum technologies
France	Established in 2021 ("Quantum Priority Research and Equipment Programme")
	Focused on long-term development through industry, research, and academic training
The Netherlands	Established in 2019 ("National Agenda for Quantum Technology")
	Focused around five major national research hubs
India	Established in 2019 (declared quantum tech. as a "mission of national importance")
	Focused on leveraging Indian technology companies
Israel	Established in 2019 (five-year National Quantum Initiative)
	Boosted through economic stimuli and ecosystem development
Singapore	Established in 2019 (Research, Innovation, and Enterprise 2025 Plan)
	Focused on quantum computing and communication technologies for automation/ smart tech
South Korea	Established in 2019 (included in 5 year Information and Communcation Technology Plan)
	Focused around a goal of a practical five-qubit system

89 Table References in Appendix B.

Key Challenges for Policymakers and Non-Technical Audiences

Beyond the fact that there are three distinct categories of quantum technologies, each with their own set of applications and characteristics, other sources of confusion for policymakers and non-technical audiences engaging in the sphere arise when discussing the functionality across the different technologies. First, because the field is so young, scientists and engineers are still exploring a wide variety of platform types, or materials capable of hosting qubits or quantum systems. Each of the proposed platforms have their own unique set of performance benefits and drawbacks, making it complicated for non-technical audiences to navigate the nuances across the different platforms. Second, there is significant hype over the theoretical advantages of quantum platforms, but there is less discussion over the obstacles to development or the practical limitations that might curb the quantum advantage over non-quantum alternatives. Discussing these factors does require a higher degree of technical knowledge, but understanding a few of the major parameters used to reference the limitations can at least provide some insight. Finally, as the field continues to evolve, challenges have arisen in defining metrics that would make it easier to compare performance across different platform types and to define acceptable requirements for deployment or operation.

These three areas are not a comprehensive list of challenges for policymakers engaging in the field, but can at least provide some technical grounding on hard-to-grasp elements that are particularly policy-relevant. This section will provide introductions and references to these topics, in order to help provide a basic level of working knowledge for policymakers. However, the relevance and focus of these three areas could change as the field evolves, and one of the most critical requirements in engaging on quantum topics is staying up to date on research efforts and changes in the field, a problem that has at least been somewhat alleviated by the rise in quantum newsletter outlets.[90]

Variability Across the Types of Quantum Host Platforms

One of the key challenges in navigating R&D trends is the sheer variety of platform types that are being pursued. Generally, these platforms are categorized based on the types of qubits and material platforms hosting them. A variety of small two-level quantum systems are used to make qubits, such as nuclei spins, ion energy levels, or photons of light. Some of these qubits are based in naturally occurring materials, such as trapped ions or neutral atoms, while others are based in artificial/fabricated systems, such as superconducting circuits and quantum dots.

[90] For example: Inside Quantum Technology (https://www.insidequantumtechnology.com/), Quantum Computing Report (https://quantumcomputingreport.com/), and The Quantum Insider (https://thequantuminsider.com/).

As Figure 4 shows, two major platforms that have thus far received the greatest volume of funding interest and research focus are superconducting and trapped ion qubits. Superconducting qubits are artificially made using macroscopic circuit components[91]. Because they are engineered using well-established circuit elements and theory, the fabrication base is already fairly robust and qubits can be customized to improve performance for specific applications.[92] However, superconducting platforms do require ultra-cold temperatures, which entails greater system control requirements, such as dilution refrigerators or other cryogenic methods.[93] Additionally, because they are artificially made, small-scale fabrication imperfections creating differences across qubits impact decoherence time, or the length of time a qubit is functional, as well as connectivity across qubits.[94]

Figure 4: Two Leading Quantum Platforms are Superconducting and Trapped Ion Qubits[95]

Superconducting	Trapped ion
•Artificially made using electric circuits components •Pros: fast operation, easy fabrication •Cons: quick decoherence, high error correction requirement, ultra-cold temperatures required •Key Industry Members : Google (US), IBM (US), Rigetti (US), Intel (US), Raytheon (US), Amazon Web Services (US), Oxford Quantum Circuits (UK), University of Science and Technology (China)	•Atoms or ions are trapped using lasers and magnetic fields •Pros: longer decoherence times, operatable at room temperatures, high connectivity •Cons: less mature fabrication techniques, slower operation, vacuum capability requirement •Key Industry Members: IonQ (US), Honeywell/Quantinuum (US/UK), Universal Quantum (UK), Alpine (Austria), Quantum Factory (Germany), EleQtron (Germany), Oxford Ionics (UK)

Conversely, trapped ions, another leading platform in Figure 4, utilize ions or atoms as the qubits by trapping them with electric or magnetic fields.[96] Because they are based on fundamental nuclear and atomic properties, trapped ion qubits are indistinguishable, and thus have longer decoherence times and higher connectivity across qubits. Some trapped ion platforms may be able to be operated at room temperature, which would ease the systems

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91 P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, "A Quantum Engineer's Guide to Superconducting Qubits," *Applied Physics Reviews*, Vol. 6, No. 021318, 2019, https://aip.scitation.org/doi/10.1063/1.5089550.

92 J. Clarke and F. K. Wilhelm, "Superconducting Quantum Bits," *Nature*, Vol. 453, No. 1031, 2008.

93 Krantz et. al., 2019.

94 Clark and Wilhelm, 2008.

95 "Chapter 5: Essential Hardware Components of a Quantum Computer," in *Quantum Computing: Progress and Prospects*, Eds Emily Grumbling and Mark Horowitz, National Academics of Science, 2019.

96 "Chapter 5: Essential Hardware Components of a Quantum Computer," in *Quantum Computing: Progress and Prospects*, Eds Emily Grumbling and Mark Horowitz, National Academics of Science, 2019.

control requirements.[97] It should also be noted that within each of these platforms, different properties may serve as the basis for measurement. For example, superconducting circuits can be operated based on phase, flux, or charge, or else a combination of factors (transmon, i.e.), while trapped ion platforms may store information in optical or hyperfine states.[98]

However, as Figure 5 shows, there are still a variety of other qubits that are under research and development, including neutral atom, quantum dot, topological, photonic, and defect qubits. Even though these qubits may have received less funding interest so far, they each still have drawn their own bases of interested stakeholders. And as can be seen through Figure 5, they also have unique characteristics, ranging from the fabrication process to the theoretical and experimental technical difficulty levels. For example, photonic qubits are unique because they use light to store information, rather than physical objects. This means that although they are less sensitive to environmental perturbations compared to physical qubits, they are also more difficult to control. Meanwhile, systems like topological qubits promise certain advantages in reducing error, but are still only at the theoretical stage and have yet to be practically observed.

Figure 5: Beyond Trapped Ion and Superconducting Platforms, a Variety of Other Types of Qubits are also Being Explored[99]

Neutral atom

- Atoms are held in arrays and operated as qubits
- Pros: by definition indistinguishable, long decoherence times, more scalable
- Cons: difficult to control atoms, hard to entangle
- Key Industry Members: QuEra (US), ColdQuanta (US), Atom Computing (US), PASQAL (France)

Quantum dot/spin

- Electron confined in a "box" and spin used as qubit
- Pros: spin has weak interaction with environment, tunable
- Cons: hard to couple, high control systems requirements
- Key Industry Members: Intel (US), QuTech (Netherlands), Origin Quantum Computing (China), USWS (Australia), Toshiba (UK)

Topological

- "Anyons" (2D particles) are braided together in 3D space
- Pros: very stable and limited error
- Cons: not yet proven to exist…
- Key Industry Members: Microsoft (US), QuTech (Netherlands)

Photonic

- Particles of light used to store information
- Pros: operate at room temperature, less sensitive to the environment, easy fabrication
- Cons: reliable gate operation is hard given insensitivity
- Key Industry Members: PsiQuantum (US), Xanadu (Canada), USTC (China), ORCA (UK), Quandela (France)

Defect qubits

- Well-characterized point defects in solid state materials
- Pros: lower control technology requirements, leverage semiconductor fab., high coherence
- Cons: defect availability in materials, defect distinguishability
- Key Industry Members: Quantum Brilliance (Australia), Diatope (Germany), Element Six (UK)

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[97] Ibid.

[98] Clark and Wilhelm, 2008.

[99] Ibid.

Thus, there is still no platform type that is clearly superior to the other types. As Figures 4 and 5 indicate, each of these architectures has its own unique set of characteristic strengths and weaknesses, depending on the materials used and the associated measurement and manipulation techniques.[100] Furthermore, direct comparison is challenging given that some are further along in development, either due to material availability or private sector interest and funding volumes, and some operate on entirely different mechanisms. Thus, although there is a slight distinction between the better-known and lesser-known platform types among scholars in the field, the possibility that the current hierarchy may change is widely accepted. Based on characteristic differences in operability, it is also entirely likely that different platforms will simply be more or less suitable for different applications in the future, with universally operating systems being comprised of hybrid systems composed of multiple types of qubits.[101]

Major Obstacles Across Quantum Technologies

Another barrier to engaging with the quantum technology field is the difficulty in understanding the practical challenges that limit the ability to fully achieve proposed theoretical advantages of quantum systems. However, understanding these limits is an important step towards separating hype from realistic expectations on quantum technologies, and is also advantageous when identifying policies to best propel progress in the field. In most research articles discussing limitations of current quantum technology progress, the main obstacles identified and parameters to designate success are decoherence, entanglement, and fidelity of operation. To some extent, the magnitude of these challenges differs based on the different qubit types. But, for now, these are three major areas that are referenced by the technical community. This section surveys what is meant by each of these terms, explains why they pose challenges to quantum technology development, and summarizes current efforts to alleviate issues arising from them.

1. **Decoherence**
   Decoherence refers to the degradations in a qubit's superposition states due to environmental perturbations or systematic instabilities.[102] These degradations lead to cumulative decoherence over longer periods of time, which can either result in a total collapse of the qubit state or a loss of information throughout time. The magnitude of the decoherence scales up with the susceptibility of a given qubit to environmental

[100] James Eckstein and Jeremy Levy, "Materials issues for quantum computation," *MRS Bulletin*, Vol. 38, October 2013.
[101] Christopher Richardson, Vincenzo Lordi, Shashank Misra, and Javad Shabani, "Materials science for quantum information science and technology," *Materials Research Society*, Volume 45, July 2, 2020.
[102] Dowling and Milburn, 2002.

noise and is inversely proportional to shielding measures use to block exposure to the quantum system.[103] To some extent, decoherence is inevitable for any operating quantum system. Thus, while shielding and selection of a qubit that does not respond significantly to exposure are both important innovation areas, error correction to account for expected decoherence in the measurement phase is another major area of research.[104] Here, the goal is to characterize the noise and expected decoherence in a system such that the associated phase shift (or the impact of the decoherence on the qubit state) can be calculated and factored in to correct for decoherence in the measurement phase.

2. Fidelity

Fidelity is another key area of concern and is related to the actual operability of quantum technology systems.[105] From a technical standpoint, fidelity refers to the probability that a technology will yield the correct outcome, or in quantum systems that a physical quantum state will match the expected or assumed quantum state.[106] In other words, it is the opposite of the error rate of a system.[107] For example, in quantum computing, gate fidelity defines the probability that a logic gate operation on qubit will yield the correct qubit state value when measured. Loss in fidelity can occur as a result of numerous mechanisms, including systematic noise, environmental noise, material defects, or random error inherent in the system.[108] Research in this area seeks to improve instrument isolation methods, targeted manipulation techniques, and identification of better materials, as well as determine better benchmarking for fidelity.[109]

3. Entanglement/Connectivity

Entanglement/connectivity is the third major obstacle that scientists are attempting to address. Harnessing entanglement and connectivity across qubits is assumed to be the major thrust for quantum technologies, and is perceived as a step that will allow for maximization of capability improvements for quantum systems compared to non-

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103 James Eckstein and Jeremy Levy, "Materials Issues for Quantum Computation," *MRS Bulletin*, Vol. 38, 2013.

104 Reviewed in: Vickram Premakumar, "Decoherence and Error Correction: Topics in Quantum Computing," The University of Wisconsin – Madison Dissertation, 2019.
And earlier in: Michael Nielsen and Isaac Chuang, "Chapter 10: Quantum error-correction," in *Quantum Computation and Quantum Information*, Cambridge University Press, 2010.

105 Richardson, Lordi, and Misra, 2020, pp. 487.

106 "Chapter 2: Quantum computing: a new paradigm," in *Quantum Computing: Progress and Prospects*, Eds Emily Grumbling and Mark Horowitz, National Academics of Science, 2019, pp. 49 – 50.

107 Ibid, pp. 49.

108 Ibid, pp. 50.

109 For example: J. T. Muhonen, A. Laucht, S. Simmons, J. P. Dehollain, R. Kalra, F. E. Hudson, S. Freer, K. M. Itoh, D. N. Jamieson, J. C. McCallum,et. al., "Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking," *Journal of Physics: Condensed Matter,* Vol. 27, no. 154205, https://iopscience.iop.org/article/10.1088/0953-8984/27/15/154205/meta.

quantum alternatives.[110] However, establishing entanglement, or points of connectivity, between qubits can be challenging in practice.[111] Improving connectivity between qubits is especially complicated given that the requirements are at odds with those to meet goals of improving coherence and fidelity; in these areas, isolation from the environment is ideal, but for connectivity, qubits must not be isolated from each other. Efforts to improve connectivity and entanglement techniques are focusing on increasing similarity between qubits (or as referenced earlier, indistinguishability) through fabrication methods, as well as ease of connectivity through architecture design for processors (including the geometrical positioning of qubits on processors in relation to each other).[112]

In addition to these three established research areas, policymakers must also survey the broader scope of challenges facing the quantum ecosystem. This must extend beyond experimental challenges, which have received the majority of focus from the technical community thus far. Policymakers should expand the scope that they consider to include theoretical/mathematical challenges at the core of the technology that will require basic research funding and resource allocation. Policymakers should also plan ahead for alleviating operational issues once the technologies become commercialized, such as by identifying potential issues for specific use cases, funding research to explore operability outside of lab settings, and supporting research that evaluates technology lifetime prospects. Finally, in looking to the far future, policymakers should also consider challenges to future scalability, including funding schemes to make the technology more economically viable, distribution options, and supply chain security. This broader spectrum of challenges is shown below in Figure 6.

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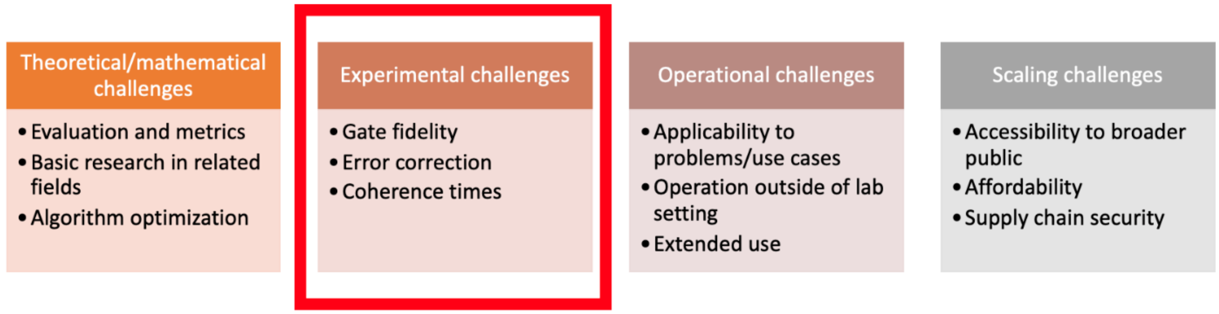
110 "Chapter 2: Quantum computing: a new paradigm," in *Quantum Computing: Progress and Prospects*, Eds Emily Grumbling and Mark Horowitz, National Academics of Science, 2019, pp. 26.

111 Zachary Eldredge, Leo Zhou, Aniruddha Bapat, James Garrison, Abhinav Deshpande, Frederic Chong, and Alexey Gorsckov, "Entanglement bounds on the performance of quantum computing architectures," *Physical Review Research*, Vol. 2, No. 033316, 2020, https://link.aps.org/doi/10.1103/PhysRevResearch.2.033316.

112 For example, discussed with respect to superconducting qubits in: Morten Kjaergaard, Mollie Schwartz, Jochen Braumuller, Philip Krantz, Joel I-J Wang, Simon Gustavsson, and William Oliver, "Superconducting Qubits: Current State of Play," Annual Reviews of Condensed Matter Physics, Vol. 11, https://arxiv.org/pdf/1905.13641.pdf.

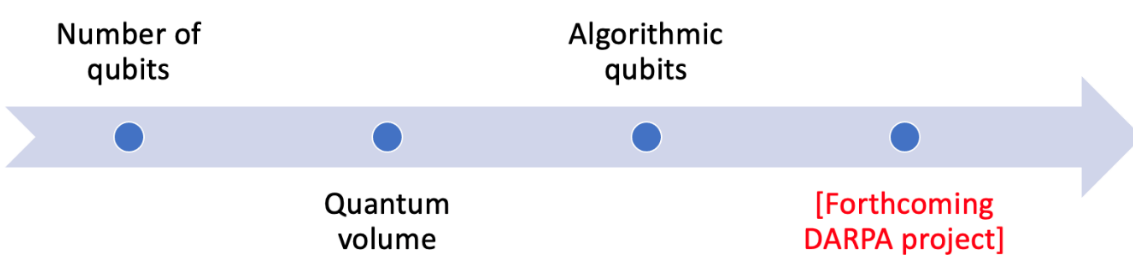
Figure 6: A Broader Scope of Quantum Technology Development Challenges



Timelines and Performance Benchmarks

Another barrier for policymakers engaging in the field is the difficulty comparing the suitability of different platforms and the stages of development (which combines both the challenge areas previously discussed). On one hand, it may seem easy to assess the sheer scaling of a quantum system, basing the determination on how many qubits have been successfully operated in a processor. However, given the qualitative factors detailed above and the different stages of development for the various platforms, a useful performance metric system should also be able to convey the relative functionality for each platform, including how robust the system is to decoherence, fidelity of operation, and error correction success. Because the field itself is still evolving, and scientists continue to identify characteristics important to parametrize quantum technologies, the determination of a metric for analysis has been a bit of a moving target, with different performance metrics being proposed and used throughout the past ten years. Figure 7 outlines the iterative metrics that have been proposed thus far.

Figure 7: Trajectory of Quantum Technology Performance Benchmarks



At the beginning of the quantum technology era, the size of the platform was the major metric of analysis. In this sense, scientists and engineers would relay how functional a system was based on the number of qubits that it could harness, and would also use this to determine whether it could outperform a traditional conventional computer (a feat referred to as "quantum supremacy").[113] However, after a few leading quantum computing companies asserted that they had developed quantum processors of certain sizes or had surpassed quantum supremacy, disagreement emerged over the qualitative dimensions of the systems, including the fidelity and decoherence of the qubits in the platform.[114]

Despite moving past these more limited metrics, defining the power of a quantum computer has remained a contentious issue given the variety of platforms currently under research, including the stage of development and the range of use cases for which they are being targeted.[115] Different companies have established their own unique terms to account for the gaps in simple qubit number counts and to specify decoherence, stability, and connectivity, among other characteristics that would meaningfully impact the performance of the processor. For example, IBM introduced the "quantum volume" metric, which is supposed to integrate decoherence, measurement fidelity, gate fidelity, and connectivity.[116] In comparison, IonQ claims that its proposed metric, the algorithmic qubit unit, builds on the quantum volume work by also accounting for the success probability in completing benchmarking algorithms and circuits.[117] IonQ derived its set of benchmarking algorithms from a recently accumulated open-source QED-C repository to establish the algorithmic qubit 1.0 for its Aria quantum computer system.[118]

Establishing an agreed-upon and well-defined metric system has also become a national security imperative. The Defense Advanced Research Projects Agency (DARPA) has earmarked funding for an industry-wide analysis and identification of a suitable metric system.[119] Beyond utility in domestic comparison, such a metric will be important as different countries compete over quantum leadership. U.S. stakeholders have countered numerous announcements by China that it has achieved certain capability levels[120] (and vice-versa[121]). Developing a better

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[113] John Preskill, "Quantum Computing and the Entanglement Frontier," WSPC- Proceedings, Vol. 1, No. 19, November 2012, https://arxiv.org/pdf/1203.5813.pdf.

[114] John Preskill, "Why I Called it 'Quantum Supremacy,'" Quanta Magazine, October 2, 2019, https://www.quantamagazine.org/john-preskill-explains-quantum-supremacy-20191002/.

[115] Timothy Proctor, Kenneth Rudinger, Kevin Young, Erik Nielsen, and Robin Blume-Kohout, "Measuring the capabilities of quantum computers," *Nature*, December 20, 2021, https://www.nature.com/articles/s41567-021-01409-7.

[116] Ryan Mandelbaum, "What is Quantum Volume, Anyways," QISKIT and IBM Medium, August 20, 2020, https://medium.com/qiskit/what-is-quantum-volume-anyway-a4dff801c36f.

[117] "Algorithmic Qubits: A Better Single-Number Metric," IonQ Announcement, February 23, 2022, https://ionq.com/posts/february-23-2022-algorithmic-qubits.

[118] Thomas Lubinski, Sonika Johri, Paul Varosy, Jeremiah Coleman, Luning Zhao, Jason Necaise, Charles Baldwin, Karl Mayer, and Timothy Proctor, "Application-Oriented Performance Benchmarks for Quantum Computing," arxiv:2110.03137.

[119] "Quantifying Utility of Quantum Computers," DARPA, April 2, 2021, https://www.darpa.mil/news-events/2021-04-02#:~:text=It%20has%20been%20hypothesized%20that,to%20machine%20learning%2C%20to%20cryptography.

[120] Charles Choi, "Two of World's Biggest Quantum Computers Made in China," *IEEE*, November 6, 2021, https://spectrum.ieee.org/quantum-computing-china.

[121] Philip Ball, "Physicists in China challenge Google's 'quantum advantage'," *Nature*, December 3, 2020, https://www.nature.com/articles/d41586-020-03434-7.

metric system could serve as one step towards increasing clarity in assessing such announcements in the future and in providing better transparency and signaling in development across national efforts. Finally, metrics will ultimately be necessary to decide whether a quantum technology is ready for deployment and to parametrize the certainty over the technology's computing, communication, or sensing ability.

Recommendations

Given the obstacles identified in this paper and current policies surveyed, there are three key areas in which the U.S. government should sharpen its quantum technology policymaking, this includes network-building, improvement of working knowledge and metrics for government assessment, and broader engagement with the R&D community.

First, the government must continue to expand its communication and feedback network. Quantum technologies will have a wide variety of applications and will touch upon the activities of nearly every government agency, on issues ranging from healthcare to economic development and national security. Improved interagency communication could allow for better transparency in communicating efforts taken by different policy branches, and a clearer allocation of tasks across the different stakeholders. Additionally, government workers should ensure that their networks include private stakeholders as well. This is important given that a significant amount of innovation in the United States is happening in the private sector, which is a relatively new phenomenon for national security-relevant technologies and requires unique governance strategies to engage with external R&D trends.[122] But because that is a unique trait of American innovation compared to other countries, it should be leveraged to the maximum extent possible. Finally, the government should build on its most recent efforts to engage allies and to share the burden of quantum technology development across interested and trusted parties. However, in identifying actors to work with, the U.S. government should consider potential signaling effects to adversaries and competitors.

Second, and an issue at the core of this primer, is the importance of improving working knowledge in the government on quantum issues. Increased awareness of quantum technologies could allow for policymakers to identify use cases that are relevant to their work, and to relay these opportunities to scientists. From an acquisition perspective, increased communication will allow for more directed development of technologies that fit government needs and priorities and improved oversight of development efforts taken by the various

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[122] Amy Nelson, "Innovation and its Discontents: National Models of Military Innovation and the Dual-Use Conundrum," CISSM Working Paper, July 2020, https://cissm.umd.edu/sites/default/files/2020-07/EmergingTechInnovation_063020.pdf.

industry stakeholders. From the private sector standpoint, increased engagement and technical education among policymakers will establish more clear expectations on security imperatives and foster trust among private stakeholders in government efficacy on quantum policymaking. Deeper working knowledge can be achieved through an influx of technical experts into government agencies and/or through internal opportunities such as workshops and classes. Meanwhile, increased transparency would benefit from continued efforts to identify evaluation standards.

Finally, as arbiters of practical use cases, policymakers should work with the R&D sector to anticipate and alleviate a broader range of obstacles that will be necessary for commercializing quantum technologies, which were identified in this primer (Figure 7). From the government's perspective, this entails funding basic research to address lasting theoretical gaps. But it also necessitates greater transparency on findings from operability testing by private sector members to better understand obstacles to eventual deployment. Finally, a combined effort by the public and private stakeholders will be needed to identify necessary supply chains for future quantum technologies and to adopt measures that will contribute to supply chain security, especially for critical hardware nodes which will be the most susceptible to adversary interference.

Conclusion

Quantum technologies are becoming an important pillar in the broader global competition over technological leadership. Within the past few years, a very clear competition to lead in the development of new technologies has emerged between the United States and China. Beyond the two military-technology "near-peers," other countries are also seeking to participate in technology competition in more narrow areas that play to their national competencies or in regional settings. The impetus for competition is that technological leadership is perceived as yielding a national security advantage through asymmetric capability improvement and potentially bestowing economic and diplomatic advantages as well. While the United States has a well-established science and technology workforce and resource pool to draw from, the government must reinforce its ability to cooperate productively with the private sector in targeted R&D areas to meet national security objectives most efficiently and effectively. Given the wide scope of applications, quantum technologies have clearly become one of these domains ripe for competition. Thus, policies to improve and streamline quantum R&D by supplementing private-led initiatives with government driven objectives could serve as a paragon for other emerging technologies, and vice versa. But, in order to navigate these strategic partnerships, the government must start by building up its working knowledge on relevant technical aspects.

APPENDICES

Appendix A: Quantum Phenomena

Below are the three main quantum principles leveraged for quantum technologies. Greater details can be found in a number of emerging handbooks and textbooks on quantum information science.[123] Beyond these principles, for greater detail on physical requirements for quantum computing, see DiVincenzo Criteria.[124]

Two-Level Quantum Systems

Because quantum information theory is based off of traditional computing systems, they harness two-level (or two-state) quantum systems. Two-level quantum systems are different from non-quantum two-level systems (or binary systems) because rather than only existing in one state or the other, quantum objects can be in some combination of the two levels. Technically, quantum systems can occur in more than two levels as well, but that would increase the complexity of the analyses. While two-level systems can be mathematically solved with well-defined linear differential equations and linear algebra based on wave functions, higher-level systems would require more involved approximation methods. Finally, in practice, two-level systems are selected when two physical, observable characteristics that are measurable and manipulable define a system, such as the spins of a nucleus or polarization of a photon.[125]

Quantum Superposition

Superposition is another main principle of quantum mechanics. Superposition signifies that quantum objects can reside in some combination of all possible states of a system at the same time. The ability to establish and manipulate qubits in superposition states is one of the core tenets of quantum technologies. Mathematically, superposition is represented by a linear combination of two state vectors. For example, if a system has state vectors $|1\rangle$ and $|0\rangle$, then

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[123] For example: Crispin Gardiner and Peter Zoller, *The Quantum World of Ultra-Cold Atoms and Light* – Book 1: Foundations of Quantum Optics, Imperial College Press, 2014.
Or: Eleanor Rieffel and Wolfgang Polak, *Quantum Computing: A Gentle Introduction*, MIT Press, 2011.
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Or: Phillip Kaye, Raymond Laflamme, and Michelle Mosca, *An Introduction to Quantum Computing,* Oxford University Press, 2007.
Or: John Preskill, *Lecture Notes for Physics 229: Quantum Information and Computation*, December 1998 (Updated 2015).
Or: Michael A. Nielsen and Isaac Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 2010.
[124] David DiVincenzo, "The Physical Implementation of Quantum Computation," *Progress of Physics,* 2000, https://arxiv.org/abs/quant-ph/0002077.
[125] For more, see Chapter 2 in Preskill, 2015.

a qubit in a state of superposition could have some non-zero distributions, α and β, in each observable state. And thus, the equation for the superposition state, $|\Psi>$, would be written as:

$$|\boldsymbol{\psi}> = \boldsymbol{\alpha}|\mathbf{1}> + \boldsymbol{\beta}|\mathbf{0}>.$$ [126]

However, it is also important to understand that quantum systems are subject to the quantum measurement principle. This means that once a system is measured, its state must collapse to one of the observable traits, rather than residing in a state of superposition (most notoriously illustrated by Schrodinger's cat). This introduces challenges when developing quantum systems, because after measurement, systems must be put back into superposition states, and accidental or erroneous measurements could disrupt calculations.[127]

Quantum Entanglement

Quantum entanglement is another major quantum principle, which defines that quantum objects may be connected such that they share characteristics, regardless of the distance between them. Albert Einstein famously referred to this phenomenon as "spooky action at a distance." Entanglement means that if an observer knows something about one entangled object, they can infer information about the other, and likewise that they can manipulate one object by manipulating the entangled pair. These properties can be used in quantum information technologies to increase complexity of calculations (dense coding), to perform error correction, to transmit information or decryption keys, or to monitor interference. While harnessing entanglement maximizes the benefits of quantum systems, it can be difficult to create and sustain in operation.[128]

[126] Nielsen and Chuang, 2015, pp. 13.
[127] Nielsen and Chuang, 2015, pp. 15.
[128] Preskill, Chapter 4, 2015.

Appendix B: References for International Governance Strategies (Table 1)

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- John Costello, "Chinese Efforts in Quantum Information Science: Drivers, Milestones, and Strategic Implications," Testimony for the U.S.-China Economic and Security Review Commission, March 16, 2017.

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